<u>Contractor's Report to the Board</u>

Landfill Facility Compliance Study Task 7 Report—Study of Emerging Technologies in Waste Management for MSW Landfills

December 2003

Produced under contract by:

GeoSyntec Consultants, Inc.
Walnut Creek, California

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1 Executive Summary

This report presents the results of work completed by GeoSyntec Consultants, Inc. (GeoSyntec) under Task 7 of the Landfill Facility Compliance Study for the California Integrated Waste Management Board (CIWMB). The Landfill Study consists of two phases. Phase I includes Tasks 1–3 (compiling a checklist of pertinent environmental regulatory requirements, developing a cross-media database inventory of 224 California municipal solid waste (MSW) landfills, and assessing MSW landfill environmental performance for the time period from January 1998 through December 2001). Phase II consists of Tasks 4–8 (these tasks include assessing the effectiveness of current regulatory requirements in controlling environmental impacts over time and identifying possible ways to improve landfill operations to ensure greater environmental protection). The purpose of Task 7 is to identify new, emerging, and advanced technologies, as well as new approaches that if applied in California could possibly improve and/or enhance the operation of California's MSW landfills. The Task 7 Report also identifies those California landfill sites included in the Task 2 cross-media database inventory where these emerging technologies have been implemented.

Four categories of emerging technologies are evaluated in this study: Pre-treatment Technologies; Landfill Design Technologies; Landfill Remediation Technologies; and Industry Standards, Certification and Guidance Documents. Within these four categories a total of 15 individual technologies are presented. The discussion of each technology includes the following, where applicable:

- A description of the technology.
- Identification of where the technology has been implemented and presentation of a case history (where available).
- Identification of research topics pertinent to the technology.
- An evaluation of the viability of applying the technology in California.
- A summary of the benefits and barriers to successful implementation of the technology.

The pertinent points discussed for each of the technologies are summarized in Table 7-A in Section 7 of this report. The applicability of the technologies in California is discussed in Section 7 and summarized in Table 7-B.

There are many factors that affect the applicability of a particular technology at a given site. Likewise, the technologies presented in this report represent a wide range of waste management activities, making it difficult to provide an across-the-board assessment of which technologies are most applicable to California. However, several of the technologies discussed in this report are recognized to have considerable potential for successful implementation in California due to ease of implementation, successful past experiences, appropriate conditions in California, in accordance with existing regulations, and so on. These technologies include:

- **Mechanical Pre-Processing:** A mechanical pre-processing system comprised of separation and shredding may be found to be cost effective and to preserve landfill space, as it may serve to both increase compaction (reduce the volume of material to be disposed) and enhance stabilization (accelerate degradation) of the waste mass following disposal.
- **Anaerobic Bioreactors:** This technology may be particularly applicable in less arid parts of California, in which a new cell is designed for the recirculation of leachate (or

other liquid) and the collection of landfill gas for the primary goal of enhancing waste stabilization (accelerating waste degradation) with the added benefit of generating additional disposal capacity.

- **Alternative Base Containment Systems:** An electrical leak detection testing is probably the most cost-effective means of enhancing the reliability (i.e., enhancing environmental protection) of Subtitle D liner systems. Encapsulated geosynthetic clay liners (GCLs) can significantly increase the shear strength of the GCL and may be particularly applicable to canyon landfills.

- **Alternative Cover Systems:** Non-barrier cover systems (i.e., monolithic evapotranspirative cover systems, capillary break cover systems, and phytoremediation cover systems), have been developed primarily with arid and semi-arid climates in mind, as are found in most parts of California, and are expected to provide equivalent or superior infiltration control compared to the prescriptive cover system in these climates. These non-barrier cover systems may also ultimately prove to be beneficial in more temperate climates due to enhancement of waste stabilization by letting the waste breathe (i.e., mitigation of the “dry tomb” effect of a geomembrane cover) if infiltration concerns can be addressed. In addition, delayed closure may be found to be applicable in many areas of California, especially in cases where there is still significant ongoing degradation of the waste mass following the active life of the landfill due to climatic conditions.

- **Landfill Gas Applications:** The most viable emerging landfill gas (LFG) application discussed in this report is the collection and re-use of LFG as a medium-Btu fuel, because minimal processing is required, capital cost is relatively low, and economic incentives may be available.

- **Leachate Recirculation:** The recirculation of leachate in an existing landfill cell for the primary purpose of improving leachate quality, but with the added benefit of enhanced waste stabilization, may be applicable throughout California if properly designed to minimize head (i.e., the pressure exerted by a column of liquid) on the liner system and minimize the potential for seeps and stability problems.

- **Industry Standards, Certification and Guidance Documents:** The standards and certifications described in this study are generally applicable in California, and can simplify regulatory compliance and oversight. Non-prescriptive guidance documents can provide the owner with a framework for design and assist regulators in ensuring quality through consistency in design methods.

It should be recognized that each of technologies presented in this report may be applicable under certain circumstances, and should not be ruled out because they have not been included in this list.

2 Introduction

This report presents the results of work completed by GeoSyntec Consultants, Inc. (GeoSyntec) under Task 7 of the Landfill Facility Compliance Study for the California Integrated Waste Management Board (CIWMB), Contract Number IWM-C9047. The purpose of Task 7 is to identify new, emerging, and advanced technologies, as well as new approaches that if applied in California could possibly improve and/or enhance the operation of California's municipal solid waste (MSW) landfills.

The federal regulatory framework for the management of municipal solid waste (MSW) generated from residential and commercial sources is established in Subtitle D of the Resource Conservation and Recovery Act (RCRA) of 1976. In 1991, the United States Environmental Protection Agency (USEPA) revised the standards of Subtitle D in 40 CFR 258 "Criteria for Municipal Solid Waste Landfills," often referred to as Subtitle D. "The intent of these regulations is to protect human health and the environment through containment of waste in engineered landfills. These landfills must be designed to minimize the infiltration of moisture into the waste, reducing the potential for the migration of contaminants into the surrounding soil or groundwater. These facilities have been termed "dry-tomb" landfills (Oden, 2002)."

"According to the USEPA (2002), approximately 231.9 million tons of MSW was generated in the United States in the year 2000. Of this amount, about 69.9% (162.0 million tons) was disposed after recovery efforts (Oden, 2002)." Most of this waste was disposed in dry-tomb landfills. Therefore, the research and development of new technologies to reduce the nation's dependence on landfill airspace is of interest to regulators and the public in general.

In addition, concerns have been raised associated with the implementation of dry-tomb landfills, most notably regarding the reduced rate of waste degradation associated with minimized infiltration. As the organic components of a waste mass degrade, the volume of the mass is reduced and organic contaminants present in the waste mass are removed in the form of leachate and landfill gas. The waste mass becomes "stabilized." By reducing the rate at which the landfill mass degrades and becomes stabilized in a dry-tomb landfill, the demand for landfill airspace increases as does the timeframe in which environmental impacts may occur. Therefore, the implementation of new technologies as alternatives to dry-tomb landfilling are also of interest.

Developments in the areas of waste handling and treatment, landfill design, landfill remediation, certification, and regulatory guidance are under consideration by regulators, owners and engineers for application in California to address the state's dependence on landfill airspace and issues with dry-tomb landfilling. However, conditions that are encountered at waste handling facilities and landfills in California, such as climatic conditions, population density considerations and site operational constraints, among others, as well as the limitations of individual technologies, may limit the applicability of some technologies. This paper presents various technologies that are being considered for application and addresses specific limitations with regard to their successful application in California.

2.1 Emerging Technologies Discussed in This Report

New, emerging, and advanced technologies surveyed in this report can be grouped into four broad categories: Pre-treatment Technologies (also referred to as "pre-disposal waste treatment technologies" in this document); Landfill Design Technologies; Landfill Remediation Technologies; and Industry Standards, Certification and Guidance Documents. Each of these categories will be discussed in a separate section. The individual technologies under these categories that are included in this study consist of the following:

- Pre-Disposal Waste Treatment Technologies
    - Mechanical Pre-Processing
        - Separation
        - Size Reduction
        - Washing
        - Baling
    - Biological Pre-Treatment
        - Aerobic
        - Anaerobic
    - Thermal Pre-Treatment
        - Incineration
        - Pyrolysis
- Landfill Design Technologies
    - Anaerobic Bioreactors
    - Aerobic/Semiaerobic Landfills
    - Alternative Base Containment Systems
        - Double Liner Systems
        - Electrically-Conductive Liners
        - White Liners
        - Tensioned and Shaded Liners
        - Inward Gradient Landfills
    - Alternative Cover Systems
        - Monolithic Soil Evapotranspirative Covers
        - Capillary Break Evapotranspirative Covers
        - Phytoremediation Covers
        - Delayed Closure
- Landfill Remediation Technologies
    - Landfill Gas Applications
    - Passive Aeration
    - Air Injection
    - Leachate Recirculation

    - Landfill Mining

- Industry Standards, Certification and Guidance Documents
    - Industry Standards
    - Certifications
    - Guidance Documents

While air injection, passive aeration and leachate recirculation may be applied to the Landfill Design Technologies category, they are discussed in detail within the context of Landfill Remediation Technologies within this report because they may be applied to either a new landfill cell during design or to existing waste disposal units.

2.2 Organization of This Report

Discussion of each of the technologies listed above will consist of the following topics, as applicable, in the following order.

- <u>General Description</u>: provides a general definition of the technology and generally describes the process and the goals of the process.
- <u>Detailed Description and Process Options</u>: provides a detailed definition of the components of the process and describes site, environmental and design considerations of implementing the technology (depending on the complexity of the technology, this topic may be omitted or combined with General Description).
- <u>Global Application of Technology and Case Histories</u>: lists countries, states and, where available, specific sites where the technology has been implemented, and, if available, provides a case history of a selected site where the technology has been implemented.
- <u>Research Studies</u>: identifies areas of research pertinent to the technology that have been or are currently being studied, and identifies areas, where applicable, for which additional research is recommended.
- <u>Technologies in Combination</u>: is included to describe potential added benefit to waste management and disposal practices of applying the technology in combination with other technologies, and provides advantages and disadvantages of applying the technologies together.
- <u>Application in California</u>: identifies environmental, engineering, regulatory and climatic constraints, as well as any other identified constraints, of applying the technology in California (further discussion in Section 2.3).
- <u>Evaluation of Benefits and Barriers:</u> provides a list of environmental and economical benefits and barriers to implementation of the technology. Technological, operational and regulatory compliance issues specific to individual technologies will also be discussed in this section, as appropriate.

A general discussion of capital and operational costs is provided in the benefits and barriers section within the context of barriers to implementation of the technology. Detailed costs are not provided.

Because the development and application of industry standards, certification and guidance documents is fundamentally different than the other technologies discussed in this study, the topics listed in this Section are not applicable. Instead, a brief description of each industry standard, certification or guidance document under consideration will be provided in Section 6, as well as an assessment of its applicability to California.

2.3 Application of Technologies in California

Of particular significance to this study with respect to the evaluation of each of the technologies discussed herein is the potential for the technology to be implemented in California. In addition to cost, which is typically the primary consideration in implementing a new technology, other constraints that may limit the implementation or effectiveness of the individual technologies in California include, but are not limited to, the following:

- environmental benefit;
- climate;
- population;
- community participation and/or acceptance;
- land-use and availability;
- material availability (i.e., construction materials);
- waste composition;
- existing regulations; and
- existing waste management practices.

In our society, implementation of new technologies is primarily cost-driven, but it should be a life-cycle cost that drives technology selection, including long-term aftercare cost and cost of potential environmental remediation in addition to start-up and operating costs. Because current MSW disposal practices appear to be generally protective of the environment, until it can be demonstrated that new technologies like MBP (mechanical and biological pre-processing) are cost-competitive they are unlikely to be implemented on a large scale. However, there are several enhancements to current technology, such as anaerobic bioreactors, delayed final capping, and alternative covers, which may reduce both short- and long-term life-cycle costs. These technologies have immediate promise and regulatory barriers to implementing them should be lowered so that they may be pursued.

The technologies reviewed in this report are discussed with respect to their applicability to California in their respective sections, and are summarized in Section 7. As part of the discussion of applicability, a review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study will be presented to identify sites in California where the technology has been proposed or implemented. This inventory may be accessed online at the following address: www.ciwmb.ca.gov/landfills/complystudy/DB/default.asp.

2.4 Glossary

The following definitions were developed to describe the terms listed here in the manner they are used in this report:

- **acidogenic:** occurring during the first stage of anaerobic degradation, characterized by the conversion of complex organic material to organic acids and other intermediate products.

- **aerobic degradation**: reduction of the waste mass by biochemical processes (ie., growth of bacteria) that occur in the presence of oxygen.
- **anaerobic degradation**: reduction of the waste mass by biochemical processes (ie., growth of bacteria) that occur in the absence of oxygen.
- **biogases:** gases generated by a waste mass through biological reactions in the waste mass; in conjunction with a landfill, biogases may be referred to as landfill gas.
- **biological clogging**: the physical clogging of pore spaces due to the growth of microorganisms resulting in a reduced flow capacity.
- **capillary break:** a zone across which capillary tension (due to molecular attraction between soil particles and water) cannot be maintained because the space between the particles is too large.
- **cogeneration:** the simultaneous production of heat and power in a single thermodynamic process.
- **convection**: dispersion of a mass through a medium by the circulation of currents.
- **cryogenic separation:** separation of materials at a temperature that is below the freezing point of both materials.
- **diffusion:** dispersion of a mass through a medium by kinetic activity in the direction of the concentration gradient.
- **dispersion:** transport and distribution of a mass through a medium by various means, including convection and diffusion.
- **emissions:** uncontrolled discharges from a landfill to air, water, or land.
- **evapotranspiration**: the minimization of infiltration of water through the evaporation and transpiration processes of vegetation planted on the ground surface.
- **fly ash**: all solids, including ash, charred papers, cinders, dusty soot, or other matter that rise with the hot gases from combustion rather than falling with the bottom ash.
- **greenhouse gas:** any gas that absorbs infra-red radiation in the atmosphere. Greenhouse gases include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), halogenated fluorocarbons (HCFCs) , ozone (O_3), perfluorinated carbons (PFCs), and hydrofluorocarbons (HFCs).
- **halide:** a binary compound of a halogen, such as chlorine, iodine, bromine or fluorine, with a more electropositive element or radical.
- **incinerator bottom ash**: the nonairborne combustion residue from burning fuel or waste in an incinerator.
- **landfill gas:** a byproduct of the anaerobic microbial decomposition of organic waste, consisting principally of approximately 50% methane, 50% carbon dioxide, and typically less than 5% nonmethane organic compounds.
- **lysimeter**: a field device containing a soil column and vegetation, used for measuring actual evapotranspiration

- **MBP (mechanically-biologically processed) waste**: the residual waste remaining after mechanical separation and biological pre-treatment has been performed.
- **mesophilic:** the range of temperature between 95 and 105 degrees Fahrenheit; the most productive temperature range for anaerobic digestion.
- **methanogenic:** occurring during the second stage of anaerobic degradation, characterized by the conversion of acetic acid and hydrogen to methane and carbon dioxide.
- **oxidize:** to remove hydrogen by the action of oxygen.
- **phytoremediation**: the direct us of living green plants for in-situ risk reduction for contaminated soil, sludges, sediments, and groundwater, through contaminant removal, degradation, or containment.
- **piezometer**: a non-pumping well, generally of small diameter, that is used to measure the elevation of the water table or potentiometric surface.
- **refuse-derived fuel**: the combustible, or organic, portion of municipal solid waste that has been separated out and processed for use as fuel.
- **residual ash**: the solid materials remaining after the completion of thermal pre-treatment (i.e., incineration) of a waste mass.
- **residual waste**: the solid materials remaining after the separation of waste or the completion of a chemical or physical process, such as digestion.
- **sorbent:** a substance that takes up and holds material by either adsorption or absorption.
- **solvent extraction:** a removal method based on the relative solubility of a substance in two immiscible liquids.
- **tensiometer:** a device used to measure the soil-moisture tension in the unsaturated zone.
- **thermophilic:** the range of temperature between 135 and 145 degrees Fahrenheit; anaerobic digestion may occur in this range, but is not a productive as in the mesophilic range.
- **waste stabilization:** the reduction in biological, chemical and physical reactions in the waste mass with time caused by the depletion of sources for the reactions. The degradation of organic matter, leaching of chemical constituents, and settling of the waste mass (i.e., reduction in void space) are examples of biological, chemical and physical components of waste stabilization.

3 Pre-Disposal Waste Treatment Technologies

As suggested by the name, pre-treatment technologies are applied after arrival of waste at the receiving center or landfill site but prior to final disposal of the waste in the landfill. The general premise of pre-treatment technologies is that treating the waste prior to final disposal will reduce the volume of waste being landfilled and/or enhance or accelerate the stabilization of the waste, reducing the long-term detrimental effects on the environment.

Pre-treatment technologies are applied most commonly in Europe and Japan, where regulations often require stabilization of waste and reduction of emissions potential prior to final disposal to minimize land-use for landfilling and reduce the potential for long-term detrimental effects on the environment. It is not uncommon for the various pre-treatment technologies to be implemented in combination, as discussed in this section.

3.1 Mechanical Pre-Processing

3.1.1 General Description

The inherent heterogeneity of MSW due to the variety of waste types and sizes constituting the waste mass has been found to inhibit the degradation of waste under typical landfill conditions. By mechanically pre-processing MSW prior to its disposal in a landfill, several types of improvements may be made to the characteristics of the waste mass:

- recyclable / reusable products may be extracted from the waste mass;
- undesirable constituents may be removed from the waste mass;
- waste types may be separated for further pre-treatment;
- closed containers may be opened to allow for enhanced degradation; and
- size reduction / homogenization of waste mass may be performed to enhance degradation and compaction.

Processes that fall under the category of “mechanical pre-processing” include:

- separation,
- size reduction / shredding,
- washing / flushing, and
- baling.

These processes are discussed in this Section. Mechanical pre-processing is often used in conjunction with biological pre-treatment, which is discussed in Section 3.2, and/or thermal pre-treatment, which is discussed in Section 3.3.

3.1.2 Detailed Description and Process Options

3.1.2.1 Separation

Waste separation includes sieving and screening processes to divide waste by size and automated and/or hand separation to segregate waste by type. To optimize a waste separation program, the incoming waste stream may need to be evaluated physically and chemically to identify the most appropriate method for beneficial use, treatment, and/or disposal of the various waste components (Biala, 2001). Recyclable materials such as glass, plastic and metal may be separated automatically or by hand at the beginning of the separation process in order to recover as much re-usable materials as possible. Hand separation may also be employed instead of mechanical separation, or as a supplement at the beginning of the process, to remove undesirables from the waste stream, e.g., potentially hazardous materials or elements that may foul the mechanical pre-treatment system.

Separation may be performed on dry waste (at the as-received moisture content), or on waste that has been wetted prior to separation. "Practical experience has shown that the separation efficiency of dry processes is generally lower than wet separation which uses a washing process (60% and 90% respectively)" (Luning, 2001). Washing processes, or "flushing", are discussed in Section 3.1.2.3.

3.1.2.2 Size Reduction

Processes to reduce the size of waste particles result in a more homogeneous waste mass, which increases both the compacted density and the degradation rate of the waste after it has been disposed in a landfill.

Various methods of reducing the particle size of waste are available, including shredder and ball mill methods. These methods typically show an increase in small particle waste (<1.6 in. or 40 mm) from 40% to 70%, with the ball mill type being most effective (Biala, 2001).

After performing size reduction (e.g., shredding) on MSW, the remaining large particle waste (> 2 in. or 50 mm) has been found to generally have a high energy content such that it is appropriate for thermal pre-treatment with beneficial use of the generated thermal energy. Small particle waste (< 2 in. or 50 mm) has been found to contain little energy but to have a high level of organic material (Muller, 2001), suitable for biological pre-treatment. These size fractions may be separated using a sieving or screening process and then further processed and treated to create a refuse-derived fuel (the larger particles) or an organic rich material (the smaller particles).

3.1.2.3 Washing

Washing (or flushing) of waste as a form of mechanical pre-processing has been developed primarily for two purposes. As a method of wet separation, flushing of waste allows for better separation of particle sizes and results in a cleaner oversize fraction from which reusable / recyclable components may be extracted. By washing the residual material from thermal pre-treatment processes, environmental quality may be improved prior to final landfill disposal. In both cases, contaminants will be carried by the wash water. Generally, the wash water is reused in the process as long as possible, and should always be treated prior to disposal.

For wet separation, water is introduced during the sieving/screening process and enhances the separation of the fine fraction of waste, which is collected in the wash water and separated out before the water is recirculated. A detailed description of a wet separation facility is described in Section 3.1.3.

Two methods of washing residual waste from thermal pre-treatment have been identified: mechanical washing and submerged washing. For both types of washing, ash and water are combined in a drum. Mechanical washing systems typically physically agitate the load for 5 to 30 minutes. Submerged washing systems inject air through the load to agitate it (Higuchi, 2001).

3.1.2.4 Baling

Baling is the process of wrapping waste, typically with flexible plastic sheeting such as thin low density polyethylene, for the purpose of minimizing exposure to the atmosphere and increasing compaction of the waste. Wrapped bales are protected from groundwater, rainwater or other liquid and the enclosed waste generally maintains its original characteristics with degradation processes inhibited (Baldasano, 2001). The waste is compacted and wrapping is performed under closed conditions, so that air and liquids are not allowed to infiltrate the waste. Baling techniques may be used either for temporary storage or transportation of waste, such as prior to application of other pre-treatment technologies, or for final disposal of waste, with waste being deposited in the landfill in wrapped bales.

Following the wrapping of waste a short period of aerobic degradation of the waste occurs, until the internal oxygen has been depleted. It would then be expected that anaerobic degradation would begin. However, observations under test conditions indicate that only very small quantities of methane are generated from baled waste (Baldasano, 2001). This lack of anaerobic degradation may be attributed to the following:

- the environment inside the wrapped bales may be too acidic to allow for microbial activity and thus methane generation; and

- the water content of baled waste may be too low to support the microbial life cycle for methanogenesis.

Therefore, as long as the integrity of the bales is maintained and moisture infiltration is minimized, degradation of baled waste is minimized.

Two types of bales are used in practice: highly compacted rectangular bales and less compacted cylindrical bales (Baldasano, 2001). Both baling methods are expected to achieve increased compaction of waste compared to traditional landfill compaction methods. For temporary or final storage, the completed bales are stacked closely to minimize air and moisture circulation around the bales. Because both types of bales have higher compaction than loose waste disposed in a landfill, they can be stacked higher and at a steeper angle. Landfilling baled waste allows for a cleaner operation, by allowing the placement of encapsulated parcels and by reducing the need for daily cover soil. However the long-term mechanical stability and environmental effects of landfilling baled wastes have not been investigated in detail.

3.1.3 Global Application of Technology and Case Histories

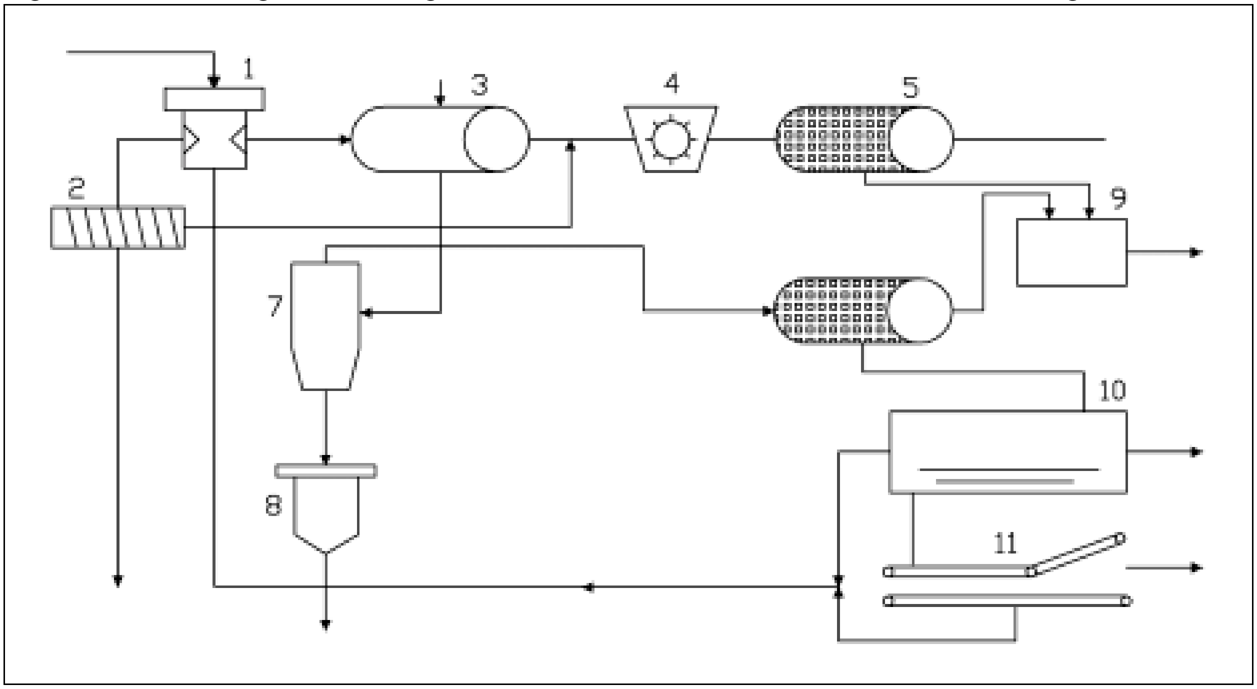
In general, mechanical pre-processing technologies are practiced primarily in Europe and Japan, where regulations often require stabilization of waste prior to final disposal to minimize land-use for landfilling and reduce the potential for long-term detrimental effects on the environment. In addition, some forms of mechanical pre-processing have been implemented at sites across the U.S. in the form of curbside collection of recyclable materials and material recycling facilities (MRFs). However, mechanical pre-processing at U.S. facilities is generally limited to separation of recyclables and prohibited wastes (e.g., household hazardous waste products). Flushing, sieving, shredding, and size reduction are rarely employed in the U.S. Furthermore, no comprehensive mechanical pre-processing facilities were identified in the United States by this study.

The following excerpts from Luning, 2001, provide a description of various mechanical pre-processing components of the VAGRON mechanical and biological pre-treatment (MBP) facility in the Netherlands.

“From the tipping floor the inlet bunker is supplied with a crane. From here the mechanical treatment starts. An overhead magnet is used to recover scrap iron from the overflow from this sieve. The undersize fraction is conveyed to the second drum sieve. The second drum sieve has openings of 45 mm. An overhead magnet removes ferrous metals from the oversize fraction of the second drum sieve (material between 45 mm and 200 mm). This iron fraction mainly consists of tin cans. The undersize fraction from the second drum sieve (material smaller than 50 mm) is called Wet Organic Fraction (WOF). Magnets are also used to recover ferrous metals from the WOF. Non-ferrous metals, mainly copper, lead and aluminum, are subsequently removed by an Eddy Current separator. Overflow from the first and second drum sieve is called Refuse Derived Fuel (RDF). This fraction contains a high percentage of paper and light plastics, which is recovered by air [separation] classification. After separation the paper/plastic mixture may be processed further.”

“On the basis of the preference for a wet separation process a specific process design was developed to meet the characteristics of the material WOF and the required specifications of the products to be separated being sand and coarse inert. The quality of these materials is intended to meet the standard for reuse as a building material. The simplified flow diagram of the washing plant is shown” in Figure 3.1.

Figure 3.1: Flow Diagram Washing Plant **Source: Luning, 2001**



"The basic operations in the washing plant can be described as follows:

1. The incoming material is transferred to the coarse inert separator (1) by conveyor line. In this separator the coarse inerts are separated from the organic and fine inert materials by making use of differences in size and specific weight. By creating upward flow of water in a specially designed column only the coarse inert materials are able to reach the lower end of the separator. From there they are removed by a partially underwater operating conveyor belt.

2. In order to remove remaining contamination, the coarse inerts [are] treated in a so called washer (2), where attached organics are removed by continuous agitation and abrasion in counter current flow with a process water stream. After this treatment the coarse inerts are dewatered over a sieve and transported into the dedicated bunker area.

3. The overflow of the inert separator is treated in a washing drumscreen (3). This function is two fold. Firstly to wash the sand and fine inert material out of the organics and secondly to dewater the incoming organics. After the washing drum the dewatered organics are further dewatered in a screw press and shredded (4). In this form with a dry solids content of 30-40% this material is given to a mixing screw (9) prior to hydraulic driven piston pump for transportation to the digestion plant.

4. The filtrate coming from the washing drum contains the sand and fine organic fraction. These fractions are separated in two consequent operations involving hydrocyclones (7) and a fluidized bed (8). The organic fraction is dewatered and combined in the mixing screw with the coarse organic material from the shredder. The sand is dewatered on a vibrating screen and conveyed into the bunker ready for reuse.

5. The process water is used as transport medium and cleaning agent. During operation the water itself will take up a number of materials, either in suspension or in solution. To be able to recycle the process water to a large extent additional process water cleaning operations are required such as sieving to remove fibers and settlement and flotation to remove light and heavy components."

"The start-up period…has demonstrated (once again) that waste or separated waste streams show a certain reluctance to be treated in a process type of way. During the start-up it became clear that relatively small amounts of disproportional material could have a significant effect on the operation of the Washing plant. Adaptations in the washing plant but also in the Mechanical Separation Plant were investigated and implemented. Items that had to be solved was the occurrence of "long sticks", the formation of twisted lumps of material and the fouling of screen decks. After debottlenecking the plant with respect to these problems, the activities were focused on the main operation of the washing plant, the removal of sand and inerts."

3.1.4 Research Studies

Studies have been performed or are ongoing to evaluate the optimization of mechanical pre-processing. In particular, areas of research that have been studied to date include, but are not limited to:

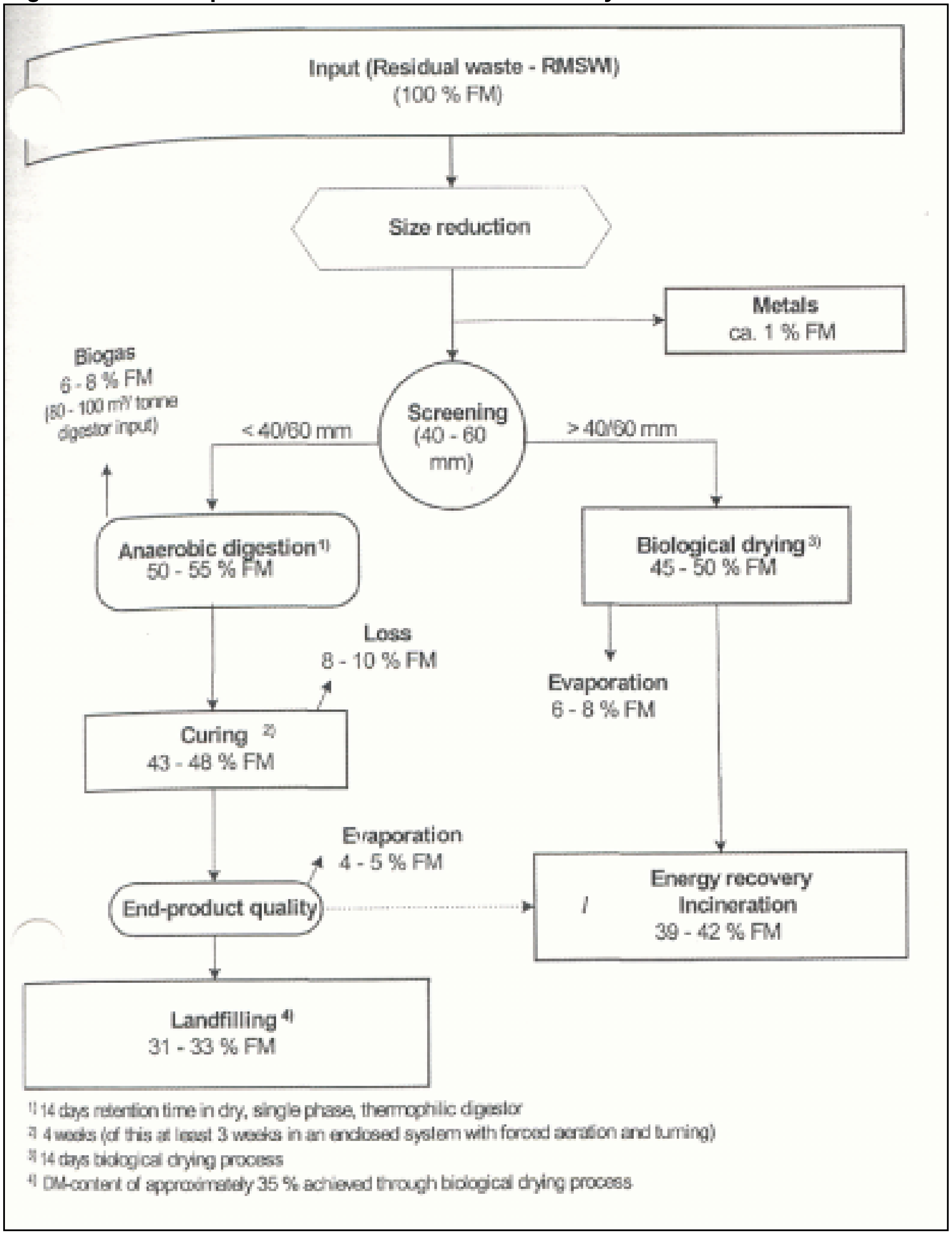
- long-term effects of mechanical pre-treatment on stabilization, gas yield and gas quality of landfilled waste;
- full-scale comparison of the behavior of MSW having received various types of pre-treatment;
- effects of washing incinerator ash on waste stabilization; and
- effects of baling waste on biogas generation.

Given the breadth of research that has been performed to date to investigate the long-term effects of landfilling mechanically-biologically pre-processed (MBP) waste, this technology may be considered field-ready for application at appropriate sites. However, the long-term effects of landfilling baled wastes have not been extensively investigated to date.

3.1.5 Technologies in Combination

It is widely recognized that the various methods of pre-treatment are the most effective when used in combination. For instance, **anaerobic or aerobic pre-treatment** is greatly enhanced when **mechanically pre-processed (separation and/or shredding)** waste is used. Likewise, **mechanical pre-treatment** of waste prior to **thermal pre-treatment** is recommended. The following flow-chart in Figure 3.2 depicts a comprehensive waste pre-treatment system, incorporating all of the pre-treatment technologies evaluated in this study (source: Muller, 2001).

Figure 3.2: A Comprehensive Waste Pre-Treatment System **Source: Muller, 2001**



In Europe, **mechanical and biological pre-treatment technologies** are being used in combination to create a soil-like, low permeability, high density, low emission potential material, called mechanical-biological pre-treated (MBP) waste, for final disposal in a landfill. Essentially, MBP technologies achieve prior to landfilling what bioreactors attempt to achieve after landfilling. The physical characteristics of MBP waste result in reduced leachate and gas generation compared to untreated MSW and allow for the immediate re-development of a landfill site following its closure. While the containment system (liner and cover) requirements for MBP waste are no different than the conventional MSW landfill, an active gas collection system is generally not required and the characteristics of MBP waste result in differences in landfill operations and construction. Recommendations for operation of a MBP landfill have been listed by Stegmann (2001), and include the following:

- alternative daily cover consisting of a reusable plastic membrane to minimize infiltration of surface water.
- high permeability layers incorporated into the waste mass every 5 to 6 feet to allow for collection of leachate.
- placement of MBP waste below optimum moisture conditions, compacted to 95% Proctor density.
- a small area of operations, with a shallow slope (less than 10%).
- waste placement in dry weather only, if possible.

Due to the inherent heterogeneity of MSW, which can limit the effectiveness of **anaerobic bioreactor landfills** and **leachate recirculation systems**, it has been suggested that MSW be **mechanically pre-processed** prior to disposal in a bioreactor. This practice has not yet been implemented in the U.S., but results of studies in Europe (Binder, 2001) suggest that mechanical pre-processing of waste can provide positive results with respect to enhancing the rate of biodegradation in a bioreactor landfill and improving moisture distribution in a leachate recirculation system. Studies have shown that waste that has been bagged prior to disposal will not experience the same level of degradation as waste that has been removed from the plastic bags and shredded or milled.

3.1.6 Application in California

Many communities in California have implemented mechanical pre-processing in the form of material recycling facilities (MRFs). These facilities are used primarily for separation of recyclable materials prior to disposal and generally do not incorporate additional mechanical pre-processing steps such as size-reduction (shredding, crushing). Size-reduction has been found to both increase initial disposal density and accelerate the degradation of waste after disposal. The primary limitations precluding the addition of shredding to the process are the cost and lack of a perceived benefit. The capital investment required to equip a facility to implement size reduction can be substantial. However, the benefits of size reduction, including additional capacity due to increased initial density and enhanced degradation, the potential for enhanced revenue from landfill gas-to-energy projects due to enhanced degradation, and decreased post-closure costs and enhanced post-closure development opportunities due to accelerated stabilization of the waste, are not widely recognized, have not, in general, been quantified, and may be difficult to quantify. Furthermore, as landfill tipping fees are generally based strictly upon weight and do not consider maximum particle size, if the MRF is not operated by the same company that operates the landfill, the benefits of shredding do not accrue to the party expending the capital cost. This dichotomy between the party accruing the cost of shredding and the party accruing the benefits may be a major barrier to implementing this technology, even if the benefits of shredding are quantified and proven to be advantageous in terms of minimizing life-cycle costs.

Baling of waste is planned or being used at several California landfills. Baling allows for increased compaction of waste prior to landfilling, reducing demand for air space. The bales can be stacked higher and at a steeper angle. Landfilling baled waste allows for a cleaner operation, by reducing the need for daily cover. However, placement of baled wastes in landfills may adversely affect the time required for environmental stability of the landfill as it prolongs degradation of wastes.

Current regulations place no barriers to implementation of this technology.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study identifies the following landfills as having planned or implemented some form of mechanical pre-processing:

- Fort Irwin Sanitary Landfill;
- Edwards AFB Main Base Sanitary Landfill;
- West Miramar Landfill;
- Potrero Hills Landfill; and
- West Contra Costa Sanitary Landfill.

However, it is likely that some form of mechanical pre-processing is performed at other landfills in California.

3.1.7 Evaluation of Benefits and Barriers

The potential benefits and barriers of implementing mechanical pre-processing technology prior to conventional MSW landfilling varies depending on the technology implemented.

Mechanical pre-processing technologies are generally optimized when used in combination with other pre-treatment and / or emerging landfill design technologies. This will increase the benefit to the environment and reduce long-term expenditures for land-use and aftercare, but will require additional upfront capital costs.

The benefits and barriers associated with individual methods of mechanical processing are discussed in this section.

3.1.7.1 Separation

Separation technology has already been implemented to some extent in the United States in many jurisdictions in the form of MRFs. Potential benefits of more comprehensive application of this technology include the following:

Environmental Protection

- collection of a higher percentage of recyclable and reusable materials than curbside collection;
- homogenization of the waste mass by sieving results in shortened degradation period of landfilled material;
- mechanical pre-processing results in a reduction of waste mass to be landfilled, increasing airspace while minimizing the long-term land use requirements;

Economic Effects

- flexibility in complexity of systems allows for control of costs versus efficiency;
- flexibility in automation of system can allow for low personnel costs.

Other Issues

- landfilling of mechanically pre-processed waste may be applied with no changes to existing Subtitle D or Title 27 of the California Code of Regulations (Title 27) landfill regulations.

The potential for barriers that may impact the successful implementation of separation technology can be summarized as follows:

Economic Effects

- relatively large upfront capital costs to design and construct the facility;
- system optimization may require coordination with other pre-treatment technologies, requiring additional upfront expenditure;
- integration with existing curbside collection of recyclables may not be cost effective; and
- potential for revenue from sale of recyclable materials is dependent on market rate for recyclables and is subject to fluctuation.

3.1.7.2 Size Reduction

Potential benefits of the implementation of size reduction technology include the following:

Environmental Protection

- homogenization of the waste mass by shredding accelerates degradation of landfilled material;
- reduction of waste mass to be landfilled due to increased compaction, increasing airspace while minimizing the long-term land use requirements;

Economic Effects

- flexibility in complexity of systems allows for control of costs versus efficiency;

Other Issues

- landfilling of mechanically pre-processed waste may be applied with no changes to existing Subtitle D or Title 27 landfill regulations.

The potential for barriers that may impact the successful implementation of size reduction technology can be summarized as follows:

Economic Effects

- relatively large upfront capitals to design and construct the facility; and
- system optimization may require coordination with other pre-treatment technologies, requiring additional upfront expenditure.

3.1.7.3 Washing

Potential benefits of the implementation of washing include the following:

Environmental Protection

- when used during separation process, results in a cleaner oversize fraction from which reusable / recyclable components may be extracted;
- washing the residual material from thermal pre-treatment processes improves environmental quality prior to final landfill disposal;

Other Issues

- when used during separation processes, allows for better separation of particle sizes; and
- landfilling of mechanically pre-processed waste may be applied with no changes to existing Subtitle D or Title 27 landfill regulations.

The potential for barriers that may impact the successful implementation of washing technology can be summarized as follows:

Environmental Protection

- produces a waste water stream that requires treatment prior to disposal; and

Economic Effects

- additional upfront expenditure on top of cost to implement the accompanying mechanical separation or thermal pre-treatment technologies.

3.1.7.4 Baling

Potential benefits of implementing baling technology include the following:

Environmental Protection

- allows for reduced emissions in the short-term and is particularly applicable if waste must be stored prior to disposal;
- temporary storage of baled waste results in a lower risk for fire than temporary storage of loose waste;
- landfilling baled wastes allows for a cleaner landfilling operation; and
- allows for increased compaction of waste prior to landfilling, reducing demand on air-space.

Other Issues

- landfilling of mechanically pre-processed waste may be applied with no changes to existing Subtitle D or Title 27 landfill regulations.

The potential for barriers that may impact the successful implementation of baling technology can be summarized as follows:

Environmental Protection

- placement of baled wastes in landfills may adversely affect the time required for environmental stability of the landfill, as it prolongs degradation of wastes;
- baled wastes have higher compaction upon landfill placement, but lower compaction after closure due to lack of decomposition and lower overburden;

- the impact of baled wastes on the mechanical stability of landfills has not been fully evaluated;

Economic Effects

- relatively large upfront capital costs to design and construct the facility;
- placement of baled wastes in landfills may adversely affect post closure development, as it prolongs the time required for environmental stability of the landfill; and

Other Issues

- requires changes in waste placement operations if used for permanent landfill disposal.

3.2 Biological Pre-Treatment

3.2.1 General Description

The biological pre-treatment of waste can be divided into two categories: anaerobic (oxygen deprived) and aerobic (oxygenated). While the biological processes of these two types of degradation are fundamentally different, as discussed below, the end result is the same: accelerated degradation and stabilization of the waste mass prior to landfilling.

3.2.2 Detailed Description and Process Options

3.2.2.1 Anaerobic Pre-Treatment

Anaerobic pre-treatment utilizes the same oxygen deprived degradation processes that typically occur within a conventional MSW landfill over a period of years. However, pre-treatment can create a controlled acceleration of the anaerobic degradation process such that it occurs over a period of a few weeks. By utilizing anaerobic pre-treatment, biogases (including methane) that would typically be formed in a landfill are captured at the source prior to landfilling and often converted to a useful form of energy.

In general, an anaerobic pre-treatment system will incorporate the following stages:

- mechanical processing of incoming waste (i.e., separation of inert and recyclable materials, size reduction, and size separation);
- mixing of incoming waste with water or leachate, as appropriate for system;
- loading of a digester and increase of temperature, as appropriate for system;
- residence in a digester for a specified period (typically a few days to a few weeks) with gas injection and/or mixing, as appropriate for system;
- collection of methane for subsequent processing and sale for beneficial use;
- dewatering of leachate from residual waste and supplemental aerobic degradation, as appropriate for system; and
- final disposal of residual waste in a MSW landfill.

There are a number of variables in the stages of an anaerobic pre-treatment system that will determine the complexity, efficiency and cost of the system. These variables are designed to fit the needs of the facility and the incoming waste. The variables include, but are not limited to, the following:

- incorporation of mechanical pre-processing or aerobic pre-treatment;
- input water content of the waste material (“wet” vs. “dry”);
- temperature during digestion (thermophilic vs. mesophilic);
- number of stages of digestion (single-stage vs. multi-stage);
- introduction of oxygen, biogas or mixing during digestion;
- digestion time;
- methane handling and beneficial use or destruction;
- addition of water or leachate during digestion; and
- incorporation of supplemental aerobic curing prior to disposal.

In general, wet multi-stage anaerobic pre-treatment systems have been found to be more efficient than dry and/or single stage processes, but their complexity over a dry single-stage system also makes them a more expensive option.

3.2.2.2 Aerobic Pre-Treatment

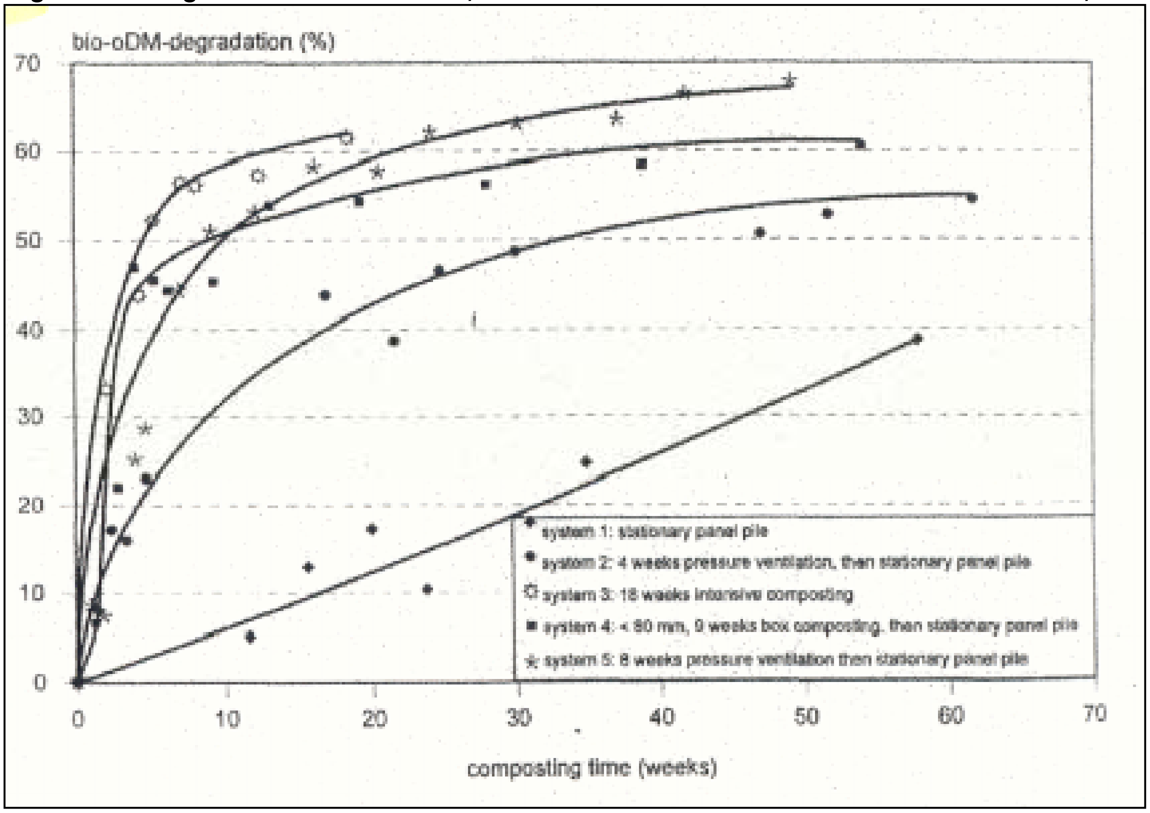
As suggested by its name, the primary difference between aerobic pre-treatment and anaerobic pre-treatment is the presence of oxygen resulting in aerobic degradation. The presence of oxygen increases the internal temperature of the waste and minimizes the development of biogases such as methane so that the primary products of aerobic pre-treatment are carbon dioxide and water (Biala, 2001).

Aerobic pre-treatment systems can be as simple as a dedicated platform where waste is allowed to cure undisturbed, also called a “compost pile”, or as complex as an integrated system incorporating pressure ventilation and mixing of the waste. The primary benefit of implementing a more complex (thus more expensive) aerobic pre-treatment system is an increase in the rate of waste degradation (or a decrease in turnover-time). “The turnover-time during aerobic stabilization depends on the optimization of biological, chemical and physical parameters, including C/N ratio [chemical composition], moisture, temperature, supply of air, rate of mixing, and so on” (Bramryd, 2001). Based on these parameters, turn-over time can be anywhere from two weeks to two years. Optimization of the waste degradation rate can be achieved by the implementation of an engineered aerobic pre-treatment system.

Simple, open composting without forced aeration is most common when the residual waste is to be landfilled. This is the most cost-effective method but it requires a large footprint and extended pre-treatment period (Soyez, 2001). It has been suggested that open piles should not be built higher than 4 m (13 ft.) to reduce the risk of fire within the waste mass (Bramryd, 2001).

Integrated composting systems are typically used where space is limited, odor emissions are problematic, and a high turnover-rate is required. The composting process is usually performed in drums or windrows, some with automated mixing and aeration. Re-cycled air can be utilized in the composting system, further reducing air emissions. Integrated composting systems can degrade organic waste by as much as 50% over a period of a few weeks (Biala, 2001). Figure 3.3 illustrates the variation of degradation (percent) over time for aerobic pre-treatment systems of varying characteristics and complexity.

Figure 3.3: Degradation versus Time, Aerobic Pre-Treatment **Source: Biala, 2001**



Unlike anaerobic digestion, which can be optimized using virtually any composition of organic waste, aerobic digestion is optimized when "green" waste (i.e., food, fresh yard waste) is mixed with coarse waste rich in cellulose (i.e., paper, dry leaves, and wood chips smaller than ¼"). The addition of coarse organic waste improves aeration of the waste mass, thus reducing the turn-over time.

3.2.3 Global Application of Technology and Case Histories

3.2.3.1 Anaerobic Pre-Treatment

Anaerobic pre-treatment systems have been developed at lab-scale, pilot-scale and full-scale in Europe and Japan, and have been generally successful. Specifically, as of 1999, five full-scale anaerobic pre-treatment systems had been implemented in Europe, one pilot-scale system had been implemented in Japan, and two systems were under construction in Canada. Many other systems were under various stages of design in Europe (Gandolfi, 1999).

Anaerobic pre-treatment systems in these cases have been developed mostly in conjunction with other forms of pre-treatment, such as mechanical separation and/or shredding and aerobic pre-treatment.

The following excerpt from Gandolfi, 1999, provides a detailed description of one full-scale multi-stage anaerobic pre-treatment system in Cagliari, Italy. At the time the paper was published (1999) the facility was under construction, with plans to come on line at the end of 1999.

"A new plant, for the treatment of 40.000 Mg/a [44,092 tons/year] household waste and 15.000 Mg/a [16,534 tons/year] sludge, is under construction in Villacidro, 70 km north of Cagliari The plant is located between a landfill, where the light/heavy fraction and the overscreen will be disposed, and a water treatment plant. The integration with the latter existing plant allowed them to use an existing digester as a hydrolyser, the gasometer and two cogenerators as well as to exchange flows between the two plants, permitting investments and operating savings. The plant block diagram is shown" in Figure 3.4.

"At first the plant can be divided into six plant areas: reception, dry-pretreatment, wet pretreatment, digestion, biogas utilization and final composting. The pretreatment operates 300 days/year for 6 hours/day, while the biological and energy production sections operate 360 days/year for 24 hours/day."

"The trucks discharge the waste in a deep bunker. Afterwards an orange-peel bucket moves them into a hopper. The bags are opened and the waste is sieved in a sieve drum. Iron is separated by magnetic separators. The overscreen is unloaded in containers, while the underscreen (<100-150 mm) is transported to the wet pretreatment."

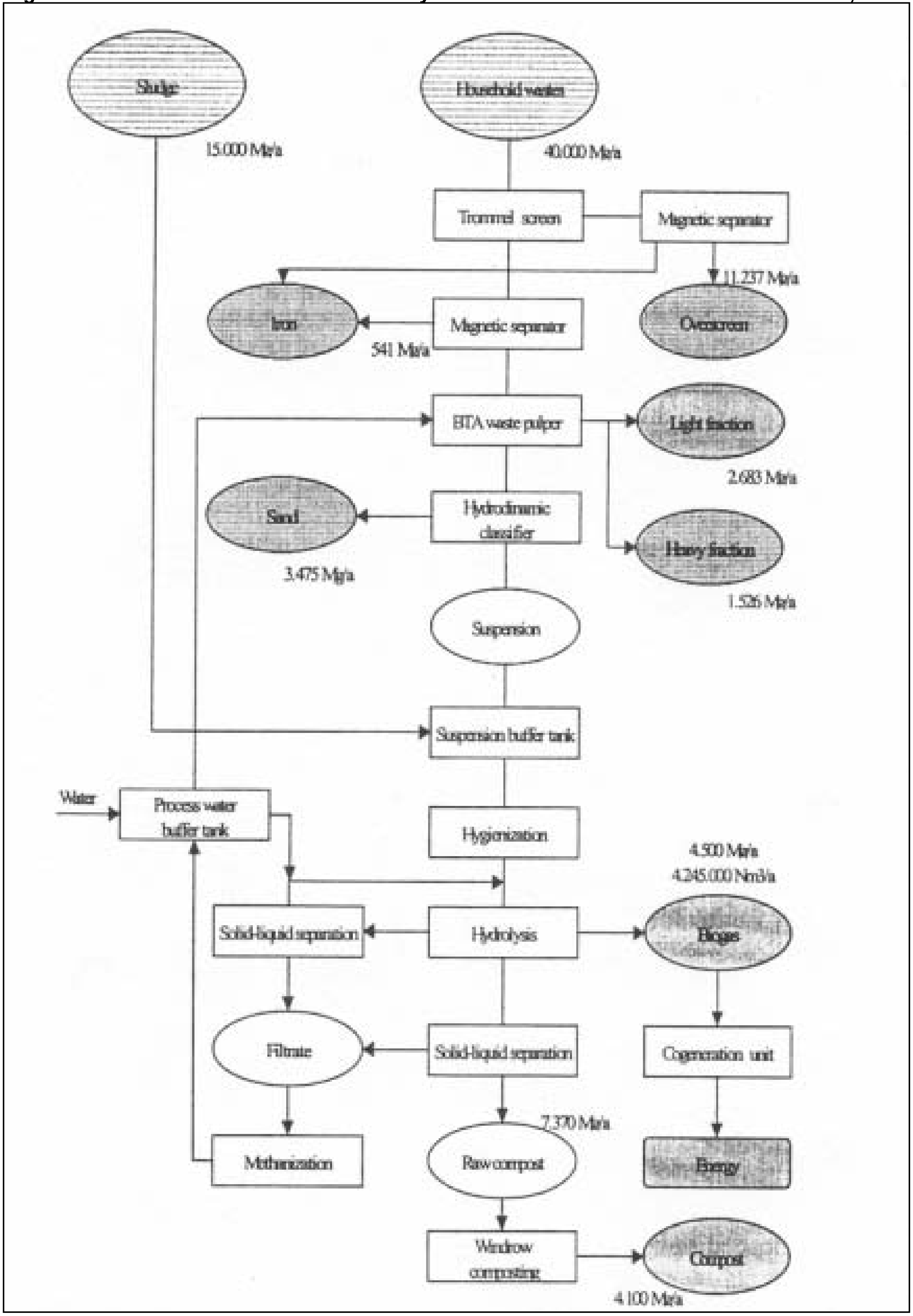
"Three 32 m3 BTA [anaerobic pre-treatment] waste pulpers produce an organic suspension by mixing and disintegrating the organic degradable from a mixture of under screen and plant process water."

"The suspension is pumped out through a sieve. The contaminants are then removed automatically by a rake (light fraction) and by a trap (heavy fraction). Sand and other fine inerts are then separated from the suspension in two hydrodynamic grit removal systems. The suspension is hygienized and treated in subsequent bioreactors for the digestion of organic matters. Solids are hydrolyzed into an hydrolysis reactor, dissolving organic solids into substances which can be easily methanized. The liquid containing readily soluble organics is turned into biogas into a methane reactor. Centrifuges are used to separate the filtrate with soluble organics and to dewater the solids, which are not hydrolyzed, thus obtaining the anaerobic compost. Separating hydrolysis and methanization, optimal growth conditions for both groups of microorganisms can be adjusted. This allows extremely rapid and extended degradation of the organics resulting in a high yield of biogas. Bioreactors are of smaller size and may be used more efficiently. Separating solids from the dissolved substances means that relatively small, high-performance methane reactors are employed."

"The biogas produced in the digestion is stored in a gasometer and then burnt in three cogenerators (cogenerating units) for the production of electric and thermal energy, used to heat up the suspension to 37º C and to drive the plant. Excess electric energy is sold to the grid."

"The anaerobic compost is matured in an open windrow composting plant."

Figure 3.4: An Anaerobic Pre-Treatment System **Source: Gandolfi, 1999**



3.2.3.2 Aerobic Pre-Treatment

Small-scale simple, open composting has occurred world-wide for centuries as a simple effective method for reducing waste mass. However, application to large-scale facilities under controlled conditions has begun only recently and has become most prevalent in Europe where regulations require stabilization of waste prior to disposal. One study performed in the United Kingdom suggests that widespread acceptance of pre-treatment technologies are hindered by existing regulations, because incentives are typically provided for a reduction of waste volume due to recycling materials but not by other methods, such as biological pre-treatment (Biala, 2001). No cases of large-scale application of aerobic pre-treatment in the United States have been identified.

3.2.4 Research Studies

Studies have been performed or are ongoing to evaluate the optimization of anaerobic and aerobic pre-treatment systems. In particular areas of research that have been studied to date include, but are not limited to:

- performance of various system options and methodologies;
- sensitivity analyses for system variables;
- quantification of organic degradation and gas generation;
- effects of pre-treatment on emissions quality improvement; and
- evaluation of biological stability.

In addition, numerous studies are being performed to evaluate more closely the full-scale performance of pre-treatment facilities and the long-term behavior of biologically pre-treated waste.

3.2.5 Technologies in Combination

It is widely recognized that the various methods of pre-treatment are the most effective when used in combination. For instance, **anaerobic or aerobic pre-treatment** is greatly enhanced when **mechanically pre-processed (separation and/or shredding)** waste is used. Some sites have performed **anaerobic pre-treatment** before **aerobic pre-treatment** to further stabilize the waste prior to final disposal. The flow-chart in Figure 3.2 (p. 12) depicts a comprehensive waste pre-treatment system, incorporating all of the pre-treatment technologies evaluated in this study (source: Muller, 2001).

In Europe, **mechanical and biological pre-treatment technologies** are being used in combination to create a soil-like, low permeability, high density, low emission potential material, called mechanical-biological pre-treated (MBP) waste, for final disposal in a landfill. Essentially, MBP technologies achieve prior to landfilling what bioreactors attempt to achieve after landfilling. The physical characteristics of MBP waste result in reduced leachate and gas generation compared to untreated MSW and allow for the immediate re-development of a landfill site following its closure. While the containment system (liner and cover) requirements for MBP waste are no different than the conventional MSW landfill, an active gas collection system is generally not required and the characteristics of MBP waste result in differences in landfill operations and construction. Recommendations for operation of a MBP landfill have been listed by Stegmann (2001), and include the following:

- alternative daily cover consisting of a reusable plastic membrane to minimize infiltration of surface water.

- high permeability layers incorporated into the waste mass every 5 to 6 feet to allow for collection of leachate.
- placement of MBP waste below optimum moisture conditions, compacted to 95% Proctor density.
- a small area of operations, with a shallow slope (less than 10%).
- waste placement in dry weather only, if possible.

Aerobic pre-treatment of waste prior to disposal in an **anaerobic bioreactor landfill** allows for accelerated degradation of the waste mass and a shorter stabilization period after the waste has been landfilled (Reinhart, 2000).

Aerobic pre-treatment of waste prior to disposal in a **leachate recirculation system** allows for increase moisture content of the waste as well as accelerated improvement of leachate quality (Barton, 2000).

3.2.6 Application in California

Anaerobic and aerobic pre-treatment are most advantageous with wastes with high organic content. Applicability of this technology must be evaluated on a site-specific basis based upon the composition of waste entering the site. Initial capital costs, in terms of equipment and space requirements as well as operating costs for material handling and fuel consumption, can be high. Benefits, including enhanced disposal capacity due to reduced disposal volumes, accelerated waste stabilization, and accelerated post-closure development, are substantial. However, it is difficult to put a dollar value of the benefits of accelerated waste stabilization and post-closure development. Due to the high initial capital costs associated with this technology, most U.S. landfill operators seem to consider the lower capital cost option of in-place biological treatment (i.e., bioreactors) as a more promising technology, even in arid and semi-arid climates where the applicability of anaerobic bioreactor technology may be limited by limited availability of sufficient water.

No technical or regulatory limitations precluding the application of these technologies in California have been identified for either of these technologies. The size and complexity of anaerobic or aerobic pre-treatment systems may be customized to fit almost any type and volume organic waste stream. The potential for odor emissions associated with anaerobic and aerobic pre-treatment should be considered when selecting a site for application. However, the primary barrier to implementation of this technology remains the high capital and operating costs and the lack of quantification of the value of the downstream benefits.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study identifies the following landfills as having planned or implemented some form of biological pre-treatment:

- West Miramar Landfill;
- Potrero Hills Landfill; and
- West Contra Costa Sanitary Landfill.

However, it is likely that some form of biological pre-treatment is performed at other landfills in California.

3.2.7 Evaluation of Benefits and Barriers

3.2.7.1 Anaerobic Pre-treatment

The potential benefits of implementing anaerobic pre-treatment technology prior to conventional MSW landfilling can be summarized as follows (Bramryd, 2001; Gandolfi, 1999):

Environmental Protection

- allows for the recovery and reuse of “green” energy (i.e., methane);
- minimizes long-term environmental effects by accelerating and controlling the development of biogases;
- results in reduction of waste mass to be landfilled, increasing airspace while minimizing the long-term effects on the environment;

Economic Issues

- flexible system complexity, allowing for control of costs vs. efficiency;
- flexible system automation can allow for low personnel costs;
- creates a potential for increased revenues from the sale of methane;

Other Issues

- applicable to all types of organic waste, regardless of pollutants or moisture content;
- applicable to a variety of waste streams in one facility; and
- requires no changes to conventional (Subtitle D) landfilling techniques.

The potential for barriers that may impact the successful implementation of anaerobic pretreatment technology can be summarized as follows:

Environmental Protection

- requires active control of odors during and after the anaerobic digestion phase;

Economic Effects

- requires an upfront capital cost expenditure to design and construct the facility;
- system optimization may require coordination with other pre-treatment technologies, requiring additional upfront expenditure;

Other Issues

- it is not effective for waste streams with low organic content; and
- requires space at the site to construct the facility.

3.2.7.2 Aerobic Pre-Treatment

The potential benefits of implementing aerobic pre-treatment technology prior to conventional MSW landfilling can be summarized as follows:

Environmental Protection

- reduces air emissions by minimizing the generation of biogases after landfilling;
- minimizes long-term environmental effects by accelerating and controlling degradation of waste prior to landfilling;
- results in reduction of waste mass to be landfilled, increasing airspace while minimizing the long-term effects on the environment;

Economic Effects

- flexibility in complexity of systems allows for control of costs vs. efficiency;
- flexibility in automation of systems can allow for low personnel costs; and

Other Issues

- requires no changes to conventional (Subtitle D) landfilling techniques.

The potential for barriers that may impact the successful implementation of aerobic pre-treatment can be summarized as follows:

Environmental Protection

- potential for objectionable odors;

Economic Effects

- relatively large upfront capitals to design and construct the facility;
- requires classification and segregation of waste to optimize degradation potential, increasing handling costs;
- system optimization may require coordination with other pre-treatment technologies, requiring additional upfront expenditure; and

Other Issues

- not effective for waste streams with low organic content.

3.3 Thermal Pre-Treatment

3.3.1 General Description

Thermal pre-treatment technologies provide a means for reducing the volume of waste that will enter the landfill, while allowing for recovery of valuable energy resources contained in MSW. Energy recovery is not required for application of thermal pre-treatment. However, it is unlikely that a new thermal pre-treatment facility would be constructed without an associated beneficial use of the thermal energy, e.g., a “waste-to-energy” facility or cement manufacture. Thermal pre-treatment technologies discussed in this study include mass burn incineration of waste and controlled, high-temperature pyrolysis of waste.

3.3.2 Detailed Description and Process Options

3.3.2.1 Incineration

Waste incineration is the thermal pre-treatment technology most commonly applied to MSW. Incineration results in the production of incinerator bottom ash and fly ash. Bottom ash consists of the heavier, less combustible materials that fall to the bottom of the combustion chamber. Fly ash is the airborne residual that exits the combustion chamber with the flue gas and is subsequently removed from the flue gas during the gas cleaning process (California Energy Commission, 1998). Energy is typically generated in the form of steam, which is fed to a steam turbine generator. In Germany, the energy generated by waste combustion has also been used for cement production.

The primary components of an incineration system include the following (California Energy Commission, 1998):

- refuse receiving, handling and storage systems;
- combustion and steam generation system (boiler);
- flue gas cleaning system;
- power generation equipment (e.g., steam turbine generator);
- cooling water condenser; and
- residue hauling and storage system.

The following excerpt from the California Energy Commission website provides a more detailed description of the typical incineration process used in California.

“Incoming trucks deposit the refuse into pits, where cranes then mix the refuse and remove any bulky or large non-combustible items (such as large appliances). The refuse storage area is maintained under pressure less than atmospheric in order to prevent odors from escaping. The cranes move the refuse to the combustor charging hopper to feed the boiler. Heat from the combustion process is used to turn water into steam, with the steam then routed to a steam turbine-generator for power generation. The steam is then condensed via traditional methods (such as wet cooling towers or once-through cooling) and routed back to the boiler.”

“The combined ash and air pollution control residue typically ranges from 20 percent to 25 percent by weight of the incoming refuse processed. This ash residue may or may not be considered a hazardous material, depending on the makeup of the municipal waste. It may be possible to avoid the production of hazardous ash by preventing the sources which create hazardous waste from entering the system. It is also possible to treat the ash. Both of these methods avoid the costs of disposal at a limited number of landfills classified as able to handle hazardous materials. Non-hazardous ash can be mixed with soils for use as landfill cover, or can be sold (or given away) for such beneficial uses as pavement aggregate.”

One variation on the typical MSW incineration facility is the refuse-derived fuel (RDF) facility. At an RDF facility, the incoming MSW is processed to remove reusable / recyclable materials, such as metal and glass, and incombustible materials, such as sand, prior to incineration. Only the resulting RDF is incinerated. In Germany, the larger-sized material generated by separation pre-processing is used as RDF due to its high energy content.

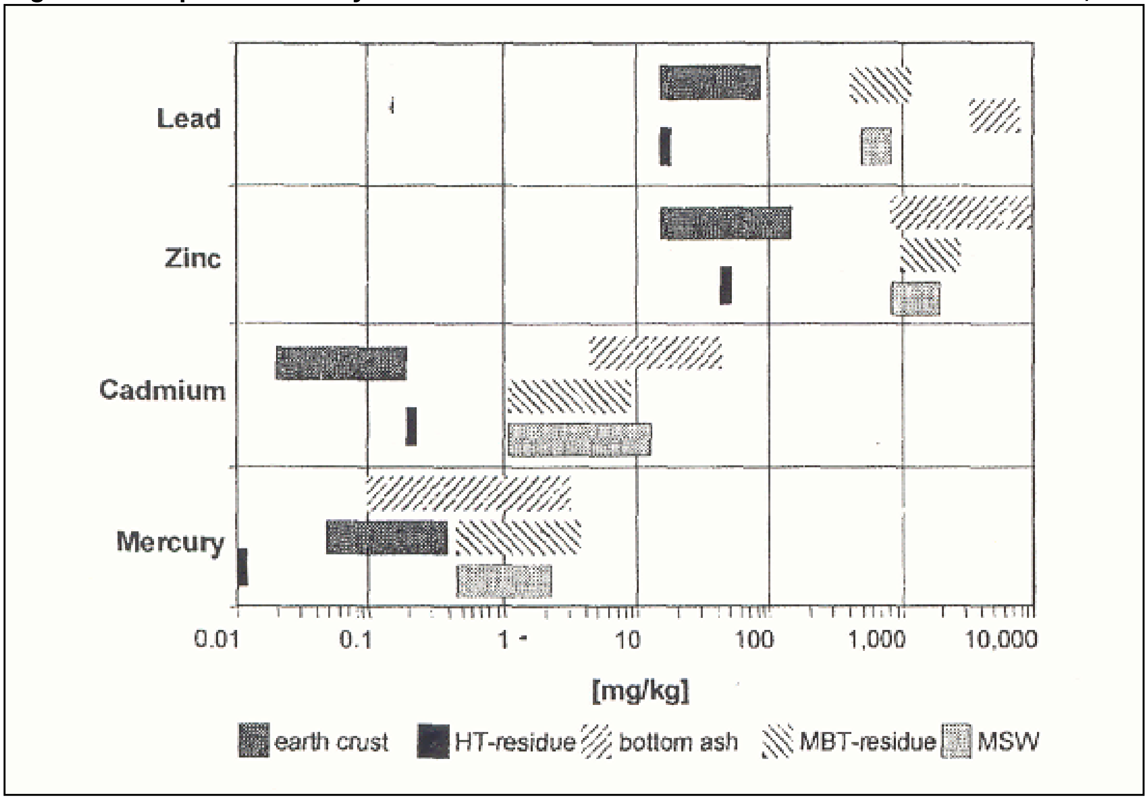
A fluidized-bed type incinerator may be used for waste-to-energy processes but only using homogenized material such as RDF. A fluidized-bed incinerator contains a layer of sand which is agitated by forced air injection. The sand is heated to temperatures on the order of 1400-1700 ºF. When the RDF is introduced it combusts very quickly. The residual ash is scraped from the sand particles by the continuous agitation of the particles, resulting in a more complete combustion process (Murphy, 2001). The residual ash is disposed at an appropriate landfill facility.

The major concerns with the use of incineration to pre-treat MSW are the control of air emissions, including dioxins that may be generated by incineration of polyvinyl chloride (PVC) and other plastics, and the production of potentially contaminated residual materials (e.g., in bottom ash). The potential contaminants of concern in the residual materials include “total carbon, particulates, chlorides, heavy metals, sulfur oxides and oxides of nitrogen (NOx)” (Murphy, 2000). Air quality regulations governing emissions of contaminants, including dioxins, have resulted in the implementation of post-incineration treatment of flue gas to bring air emissions to an acceptable, controlled level.

Without treatment, residual materials from incineration may be classified as hazardous and require disposal in a designated Subtitle C landfill. However, many of the contaminants of residual materials may be reduced using simple ash-treatment technologies. Although treatment may allow residual materials to be disposed in a Subtitle D landfill, the long-term potential for heavy metals to be leached from residual materials remains a concern. While one study suggests that fresh incinerator bottom ash has a considerably higher leaching potential than aged (1.5 to 12 years), carbonized incinerator bottom ash (Flyhammar, 2001), another study suggests the contradictory conclusion that remobilization of heavy metals from incinerator bottom ash may occur in the long-term (Doberl, 2001). A comparison of the potential for long-term impacts from heavy metals is illustrated in Figure 3.5, which depicts heavy metal concentrations for various waste types as well as typical background values.

An alternative to landfill disposal of residual ash is recycling for use as a construction material. After the removal of deleterious soil, the ash may be mixed with soil for use as aggregate in road construction or as lightweight backfill behind retaining walls. However, similar to landfilling, there are concerns regarding the leaching potential of heavy metals in residual-ash derived backfill or aggregate that must be addressed if these residual ash-derived materials are to be put to beneficial uses.

Figure 3.5: Impacts of Heavy Metals from Incinerator Bottom Ash Source: Doberl, 2001



3.3.2.2 Pyrolysis

Pyrolysis is the thermal degradation of waste under controlled conditions at high temperatures in the absence of oxygen. This process recycles the energy contained in the biomass portion and unrecoverable plastic portion of MSW (Hucks, 2002), and produces recoverable gases, oils and solids in addition to heat energy and ash. For example, the conversion of wood to charcoal is a type of pyrolysis (Juniper, 2001).

The production of potentially useful materials represents the primary advantage of pyrolysis over mass burn incineration. A secondary benefit is the reduction in detrimental effects on the environment. Because pyrolysis occurs in a closed vessel, uncontrolled air emissions are eliminated. Because most of the by-products are recovered and reused, the volume of residual ash requiring disposal is significantly reduced.

Specific products that may be derived from the pyrolysis process include, but are not limited to, the following (Juniper, 2001; California Energy Commission, 1998):

- gases, oils and char for use as fuel;
- gases, oils and char for use as petro-chemical feedstock;
- recycled metal alloys;
- carbon black; and
- hydrogen.

So far, the implementation of pyrolysis and the recovery of these products has been found to be generally cost prohibitive. However the benefits of material recovery and environmental protection to meet regulatory requirements may offset the cost.

To date, pyrolysis has been applied primarily to the thermal pre-treatment of agricultural and forestry residues, MSW, and post-recycling residues such as electrical and electronic scrap, tires, plastic waste and packaging (Juniper, 2001). However, "the operational reliability" of pyrolysis for the thermal pre-treatment of unsegregated MSW has not been verified (Juniper, 2001).

3.3.3 Global Application of Technology and Case Histories

3.3.3.1 Incineration

Mass burn and RDF incineration technologies have been implemented in Europe, Japan, and North America. In the U.S., "approximately 112 Waste-to-Energy facilities in 31 states process nearly 32 million tons of MSW annually. This MSW is delivered from 1,703 communities and represents almost 15% of the total generated in the United States" (Puzio, 2000). In 1998, there were six MSW mass burn facilities operating in California, listed below (California Energy Commission, 1998):

- City of Long Beach (SERRF), MSW, online since 1992;
- Gerber Compressor Station, MSW (Cogen), online since 1986;
- Commerce Refuse-to-Energy, MSW and RDF, online since 1990;
- Modesto Energy, MSW and tires, online since 1991;
- Covanta Stanislaus Inc. (Stanislaus Waste Energy), MSW, online since 1992; and
- [Confidential Site], MSW and waste gas, online since 1992.

It should be recognized that this list includes mass-burn facilities, which may or may not implement energy recovery. For example, the City of Long Beach facility listed above has not incorporated energy generation in its thermal pre-treatment process. It should also be recognized that according to this California Energy Commission compilation no mass-burn facilities have come online in California since 1992. This can likely be attributed to California's stringent air quality regulations.

3.3.3.2 Pyrolysis

Industry reports indicate that there are more than 100 facilities worldwide, either online or under construction, which utilize pyrolysis thermal pre-treatment technologies. In most cases, however, the history of these facilities spans less than 5 years. No facilities in North America have been identified that use pyrolysis in conjunction with post-process material recovery of MSW. One site in Minnesota utilizes high-temperature, starved-air incineration (e.g., pyrolysis). However, descriptions of this site do not indicate that material recovery is being performed (Lucido, 2000; Wilson, 2000).

One facility utilizing pyrolysis for energy recovery is being implemented in Wollongong, New South Wales, Australia. This facility "has been developed to provide Wollongong City Council and the community with a cost effective and environmentally beneficial solution to the issues associated with the disposal of household waste" (Brightstar, 2003).

The following excerpts describe the Solid Waste Energy Recovery Facility (SWERF®) developed by Brightstar Environmental. This product is being implemented at the Wollongong facility.

> The facility "is made up of three integrated components - waste pre-treatment and separation, advanced thermal conversion and electricity generation." "Waste pre-treatment involves the receival of the waste which is then sterilised with steam in an autoclave (with heat and pressure). This process is like cooking the waste in a pressure cooker. The 'cooked' waste pulp is then separated through a series of screens, trommels and magnets to remove recyclables. Steel, aluminium and rigid plastics are recovered for recycling and a pulp is produced which consists mainly of organic material. This pulp is then washed to remove sand and glass that can be further processed for use in a number of beneficial applications. The washed pulp is dried in preparation for thermal conversion.
>
> "Thermal conversion, commonly known as gasification is the next stage of the process." "The washed and dried organic pulp is fed into a sealed metal tube and heated from the outside at a high temperature. There is no air introduced into the tube and this prevents the contents from burning (which would be incineration). This process converts the elements to an energy-rich gas (synthesis gas) and a solid residue. The solid residue is further reformed in a char gasifier to produce additional synthesis gas and an inert ash that can be landfilled or used in other applications such as in masonry products. The gas is cleaned in preparation for it to be used in the power generation equipment.
>
> "The synthesis gas can be used as a fuel for power generation in a similar manner to landfill gas. The renewable electricity produced by using the synthesis gas in internal combustion engines is supplied to the local electricity distribution grid" (Brightstar, 2003).

"The waste processing building [at Wollongong] is only slightly larger than the size of an olympic-sized swimming pool. The entire site is approximately 120 metres [394 feet] long by 100 metres [328 feet] wide." The facility "occupies significantly less than a landfill site of equivalent capacity" (Brightstar, 2003). "The plant is able to process waste 24 hours a day. All waste…is contained under one roof."

The facility "at Wollongong is a staged project. The first and current stage allows for 30,000 tonnes [33,069 tons] per annum of household waste to be processed and has the capacity of 5.4 MW" (Brightstar, 2003). The first stage includes performance testing of the facility, which is expected to occur during 2003. If performance testing is successful, Stage 2 will commence, which will expand the plant capacity to 150,000 tonnes [165,347 tons] per annum. Stage 2 is expected to be completed in 2004. "The key changes in the plant to upgrade it to 150,000 tonnes [165,347 tons] per annum capacity are:

- Two additional autoclaves;
- Additional pulp washing, drying and storage equipment;
- Four additional gasifiers and associated gas conditioning modules;
- Eight additional power generation units; and
- Additional civil and building works" (Brightstar, 2003).

"At full capacity, the [facility] … is expected to provide electricity for around 24,000 homes, while achieving a 90% reduction in waste to landfill" (Brightstar, 2003).

3.3.4 Research Studies

3.3.4.1 Incineration

Studies have been performed or are ongoing to evaluate the optimization and effects of mass burn incineration as a pre-treatment of MSW. In particular areas of research that have been studied to date include, but are not limited to:

- leaching potential of residual ash and ash-derived products;
- benefits comparison with other pre-treatment technologies;
- emissions potential of various waste streams, such as MSW with a high content of polyvinylchloride (PVC);
- performance of individual components, especially emissions reduction components;
- physical characteristics of residual ash;
- effect of incineration on biological stability of waste mass; and
- structural and environmental impact of using incinerator bottom ash as a construction material.

3.3.4.2 Pyrolysis

Few studies have been identified to evaluate the optimization and effects of pyrolysis for the treatment of MSW prior to landfilling. However, particular areas of research that have been studied to date include, but are not limited to:

- comparison of long-term effects of high-temperature residual waste to incinerator bottom ash, MBT residual waste and untreated MSW; and
- structural and environmental impact of using high-temperature residual waste as a construction material.

Because pyrolysis has only recently begun to be applied to MSW, data regarding operational experiences, recovery benefits and long-term environmental effects of residual waste disposed in MSW landfills is limited and inconclusive. It is recommended that additional research be performed (Doberl, 2001) prior to widespread acceptance of this technology.

3.3.5 Technologies in Combination

It is widely recognized that the various methods of pre-treatment are the most effective when used in combination. For instance, **mechanical pre-treatment** of waste prior to **thermal pre-treatment** is recommended. Figure 3.2 (p.12) depicts a comprehensive waste pre-treatment system, incorporating all of the pre-treatment technologies evaluated in this study (source: Muller, 2001).

3.3.6 Application in California

Thermal pre-treatment in the form of incineration has been implemented at several sites in California. However the widespread application of this technology is dependent on several factors including the composition of the waste stream, local air quality regulations, and the potential for detrimental effects on the environment from the disposal of incinerator bottom ash.

California’s metropolitan areas have been designated “air quality non-attainment zones” by the USEPA. Implementation of thermal pre-treatment technologies in these areas may be restricted or may require “air pollution credits.”

The potential for detrimental effects on the environment may be reduced and air quality regulations may be met by the implementation of pyrolysis in lieu of mass-burn incineration. The use of pyrolysis has the added benefit of reducing the volume of residual material to be landfilled. However, to our knowledge, an integrated system of pyrolysis and material recovery has not been applied to MSW on a large-scale.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study does not identify any landfill sites in California are performing thermal pre-treatment. However, several off-landfill thermal pre-treatment facilities were identified in Section 3.3.3.

3.3.7 Evaluation of Benefits and Barriers

3.3.7.1 Incineration

The potential benefits of implementing mass burn incineration pre-treatment technology can be summarized as follows:

Environmental Protection

- results in reduction of waste mass to be landfilled, increasing airspace while minimizing the long-term effects on the environment;
- results in a reduction of landfill gas emissions;
- RDF process allows for recovery of recyclable and reusable materials in waste stream;
- potential for use of by-products (e.g., fly ash) as construction material to further reduce landfill airspace requirements;

Economic Effects

- creates a potential for increased revenues from sale of energy;
- potential for use of by-products (e.g., fly ash) as construction material to generate revenue; and

Other Issues

- requires no changes to conventional (Subtitle D) landfilling techniques.

The potential for barriers that may impact the successful implementation of mass burn incineration pre-treatment can be summarized as follows:

Environmental Protection

- emissions may require treatment;
- untreated residual waste may be classified as hazardous and require disposal in Subtitle C landfill;
- long-term environmental impact of treated residual waste (incinerator bottom ash and fly ash) disposal in Subtitle D landfills has not been verified;

Economic Effects

- large upfront capital costs to design and construct the facility;
- system optimization may require coordination with other pre-treatment technologies, requiring additional upfront expenditure;
- potential for revenue from energy sales is dependent on market rate for energy and is subject to fluctuation;
- incorporates mechanically engineered systems that require ongoing maintenance and repair, with potential long-term costs.

Other Issues

- emissions may require offsets to satisfy air quality regulations (as an alternative to treatment);
- not effective for construction debris or other waste with high inert material content; and
- incorporates mechanically engineered systems that require ongoing maintenance and repair, affecting site operations.

3.3.7.2 Pyrolysis

The potential benefits of implementing pyrolysis pre-treatment technology can be summarized as follows:

Environmental Protection

- eliminates uncontrolled air emissions, contrary to other methods of thermal pre-treatment;
- results in reduction of waste mass to be landfilled, increasing airspace while minimizing the long-term effects on the environment;
- results in a reduction of landfill gas emissions;
- lower potential for long-term detrimental impacts to the environment, when compared to landfilling incineration bottom ash, MBT residual waste or untreated MSW (Doberl, 2001);

Economic Effects

- creates a potential for increased revenues from sale of energy and recovered by-products;

Other Issues

- requires no changes to conventional (Subtitle D) landfilling techniques; and
- is easily integrated with other pre-disposal waste treatment technologies (Hucks, 2002).

The potential for barriers that may impact the successful implementation of pyrolysis technology can be summarized as follows:

Environmental Protection

- most existing facilities are less than five years old, thus long-term operational and environmental issues have not yet been identified;

Economic Effects

- large upfront capital costs to design and construct the facility;
- system optimization may require coordination with other pre-treatment technologies, requiring additional upfront expenditure;
- potential for revenue from sale of energy and recovered materials is subject to fluctuation;
- incorporates mechanically engineered systems that require ongoing maintenance and repair, with associated costs;

Other Issues

- the technology is unproven on a commercial scale;
- not effective for construction debris or other waste with high inert material content; and
- incorporates mechanically engineered systems that require ongoing improvements to meet ever-changing regulatory requirements.

4 Landfill Design Technologies

New and emerging landfill design technologies considered herein include technologies to both improve the characteristics of the landfill waste and to enhance the waste containment system. The primary technology for improvement of the characteristics of the landfill waste considered herein is anaerobic bioreactor technology. Aerobic bioreactor technology, which can also be used to improve the characteristics of landfilled waste, is noted here but discussed in detail in the next chapter, because of its similarity to the air injection process. Technologies for improving the waste containment system discussed herein include advanced and alternative base containment and cover systems and delayed landfill closure. Advanced and alternative base containment systems discussed herein include double liner systems, inward gradient landfills, conductive geomembrane, white geomembrane, tensioned geomembrane, and encapsulated geosynthetic clay liners. Advanced and alternative cover systems discussed herein include monolithic and capillary break evapotranspirative cover systems, phyto-covers, and exposed geomembrane cover systems.

4.1 Anaerobic Bioreactor

4.1.1 General Description

The following general definition for the term “bioreactor” has been proposed by the Solid Waste Association of North America (SWANA):

“A bioreactor landfill is any permitted Subtitle D landfill or landfill cell, subject to NSPS/EG, where liquid or air, in addition to leachate and landfill gas condensate, is injected in a controlled fashion into the waste mass in order to accelerate or enhance biostabilization of the waste.” (SWANA, 2001)

This definition could include recirculation of leachate or other liquid into an existing landfill cell not specifically designed for that purpose, which is discussed in Section 5.4 of this report. Therefore, for the purposes of this study, alternate definitions of the terms “anaerobic bioreactor” and “leachate recirculation” have been adopted. The term “anaerobic bioreactor” is used to describe a new landfill or landfill cell that has been specifically designed to allow for the injection of liquid (including leachate) to enhance biodegradation of organic components of the waste mass, which in turn accelerates stabilization of the landfill and the generation of landfill gas. The term “leachate recirculation” is used to describe the injection of leachate (or other liquid) into an existing landfill cell for the primary purpose of handling leachate generated at the site and does not necessarily suggest that the leachate is injected in a controlled manner to enhance microbial activity or that the containment system was specifically designed for the purpose of liquid injection. The definition proposed by SWANA also includes the injection of air, creating an aerobic landfill environment, which is noted in Section 4.2 and discussed in detail in Section 5 of this report.

Unlike the traditional “dry” landfilling methods prescribed by existing U.S. regulations, the anaerobic bioreactor method enhances the degradation of waste prior to closure of the landfill, reducing degradation potential of the material following closure and thereby reducing the long-term effects on the environment. By injecting liquids into the landfill to achieve an optimized moisture content of the waste mass based on its characteristics, oxygen deprived methanogenic biodegradation of organics in the waste mass is enhanced, resulting in stabilization of the waste mass and accelerated production of landfill gases (i.e., methane and carbon dioxide).

4.1.2 Detailed Description and Process Options

The primary components of an anaerobic bioreactor include the liquid injection system and the gas collection system. Liquid injection can be performed using a variety of methods including trenches, wells, ponds and leach fields. Because landfill gas generation is expected to be accelerated in an anaerobic bioreactor, a gas collection system is typically installed in conjunction with the construction of the landfill cell and with a higher capacity than systems currently installed in typical MSW landfills. Although proper design of an anaerobic bioreactor landfill should not result in increased fugitive emissions, an emissions monitoring system is generally installed to monitor performance of the landfill containment and control systems.

In addition to the design of the primary components of an anaerobic bioreactor listed above, consideration must be given to waste characteristics and landfilling procedures that may vary from typical waste characteristics and standard landfilling procedures as practiced in the U.S. In particular, consideration must be given to:

- waste heterogeneity and organics content;
- waste moisture content and the related effects on landfill stability;
- availability of liquid for injection;
- site climate conditions;
- leachate collection and recovery system (LCRS) design;
- waste placement procedures;
- daily cover characteristics;
- in-place waste temperature; and
- emissions monitoring and control during waste placement.

4.1.2.1 Liquid Injection System

Although various methods of liquid injection have been attempted, including horizontal trenches, vertical wells, ponds and leach fields, it seems that the greatest success has been achieved using horizontal trenches with piping. The horizontal piping system allows for a more diffuse distribution of liquid through the waste mass than the other methods.

Vertical liquid injection wells have been associated with several problems, including (i) a concentrated wetting front around the injection well, resulting in preferential flow paths and a large differential in degradation across the landfill, and (ii) uneven settlement of the waste mass, resulting in ponding of surface water around the well head. Likewise, surface application of liquid in ponds or leach fields has encountered problems with differential settlement due to the difficulty in controlling infiltration of surface water, the formation of preferential flow paths through the waste, and odor control.

Horizontal trenches for liquid injection are typically constructed in the waste as the site is filled, with the trenches constructed as closely as one layer per lift (approx. 20 ft.). Injection piping is laid in the trench and the trench is backfilled with a coarse material, such as granular soil or tire chips. The trench sizing and spacing and pipe diameter is evaluated on a site-specific basis, and is dependent on various factors including the characteristics of the waste. As construction of the landfill progresses, the bioreactor may be designed so that the function of the horizontal piping layers changes. For example, the purpose of deeper layers of piping, which were originally installed at the surface of the waste for injecting liquid, may be changed to gas extraction as degradation in these deeper layers progresses and the need for gas extraction increases.

The design liquid injection rate in an anaerobic bioreactor is dependent mainly on the in-place moisture content and permeability of the waste mass (including daily cover). Under laboratory conditions, the optimum moisture content for anaerobic degradation is on the order of 40%. This moisture content is generally above the field capacity of MSW under typical field conditions, which is expected to be between 25 and 30%.. However, in practice liquid is generally injected at a rate just slightly above the rate required to achieve field capacity. As some liquid is expected to be lost in the system through the unavoidable channelization of liquid in some areas, this results in an overall moisture content near field capacity. If the waste mass has an overall moisture content near field capacity, an increase in leachate generation is not expected since the liquid injected is maintained within the waste mass. However, as the waste mass consolidates, the pore volume decreases and the field capacity goes down, resulting in the generation of leachate.

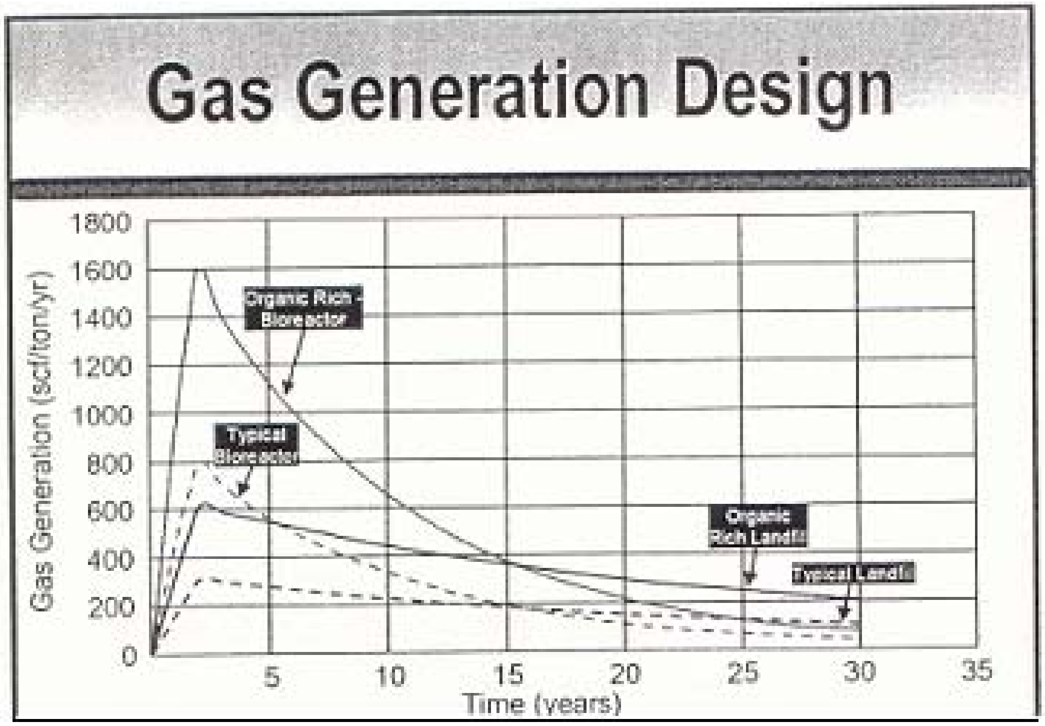
Experience indicates increased rates of liquid injection, to rates well exceeding field capacity of the waste mass, may result in detrimental effects on the stability of the waste mass as well as the development of preferential flow paths (as a result of waste heterogeneity and injection method). High moisture content and preferential flow paths can cause increased pore pressures in the waste mass (either localized or global throughout the mass), resulting in a decreased factor of safety against slope failure. The potential for increased pore pressures within the waste mass under interim as well as long-term conditions should be carefully considered during design of the liquid injection system. Pore pressure monitoring may be considered for bioreactor landfills with high liquid injection rates to mitigate stability concerns.

4.1.2.2 Gas Extraction System

The primary components of the gas extraction system in an anaerobic bioreactor landfill are essentially the same as a typical gas extraction system, with a few differences. Construction of the gas extraction system at a anaerobic bioreactor landfill always happens concurrently with the construction of the landfill, instead of during closure. Because of the accelerated generation and increased volumes of landfill gas caused by the bioreactor, the system must be installed earlier and with a higher capacity than the traditional system. Figure 4.1 compares landfill gas generation rates from a typical MSW landfill to those expected from an anaerobic bioreactor landfill.

Traditional gas extraction systems are comprised primarily of a gas collection layer beneath the cover system and vertical gas extraction wells installed at intervals across the landfill. Because gas extraction must be performed concurrently with the construction of the landfill, the preferred method for extracting gas from an anaerobic bioreactor landfill incorporates the use of horizontal piping installed in layers within the waste mass. The horizontal system provides a more evenly distributed collection system and reduces the need for a collection layer at the surface by capturing the gas where it is generated deeper within the waste mass. With a coordinated design and construction effort, it may be possible to utilize piping originally installed for liquid for gas extraction as filling of the site progresses. As the height of the waste mass increases, the increase in overburden stress and settlement of the waste mass may result in disruption of the of the horizontal gas extraction well pipes in the lower layers due to differential settlement of the waste mass. Therefore, vertical gas extraction wells may be used to supplement the horizontal gas extraction well system.

Figure 4.1: Anaerobic Bioreactor Gas Generation Design



Depending on the characteristics of the waste mass and the volume of the bioreactor, in an anaerobic bioreactor landfill a sufficient volume of "green" energy in the form of methane is generally expected to be produced during operations such that beneficial use is economical. Therefore, during the design of the gas extraction system, options for reuse, including on-site reuse and sale to the local energy market, should be incorporated into the design.

4.1.2.3 Emissions Monitoring System

The accelerated gas generation caused by an anaerobic bioreactor landfill is accompanied by an increased degradation during the life of the landfill, generally resulting in a shortened post-closure care period. As for a traditional MSW landfill, emissions at the landfill should be monitored during its active life and into the post-closure care period until it no longer presents a threat to the environment. Monitoring programs should include groundwater quality, surface water quality and air quality.

Although generation of leachate beyond the design capacity of the leachate collection and removal system is not expected, the injection of liquids into the waste mass gives rise to an increased concern for emissions to soil and groundwater. Therefore, as in all landfills, a groundwater monitoring program to monitor the performance of the landfill containment system is an essential component of the anaerobic bioreactor landfill.

Unlike a traditional landfill, where a concerted effort is made to minimize the volume of surface water in contact with the waste for reasons of surface water quality and leachate production, the purpose of the anaerobic bioreactor landfill is to increase the in-place moisture content of the waste mass to an optimal level to enhance degradation. Therefore, surface water generated at the site may be collected and used for injection if the design allows.

Although a properly designed landfill gas extraction system for an anaerobic bioreactor landfill should be as effective, if not more effective, than a system designed for a traditional MSW landfill, the increased and accelerated production of landfill gas results in an increased concern for uncontrolled emissions, especially prior to final closure. Therefore, as in any landfill, a landfill gas monitoring program should be established during filling to monitor the performance of the landfill gas extraction system.

4.1.2.4 Other Engineering Considerations

In addition to other site-specific considerations not discussed here, the following elements should be given special consideration during design of an anaerobic bioreactor landfill.

Waste Characteristics

"The microbial degradation processes in landfills predominantly depend on waste characteristics, moisture content, temperature, pH, the availability of nutrients and microbes, and the presence or absence of inhibitors" (Binder, 2001 and El-Fadel et al., 1995). To allow for optimization of the system, it is recommended that these parameters be monitored during and after construction of the anaerobic bioreactor landfill through the installation of monitoring stations in the waste and analysis of landfill gas and leachate collected from the landfill.

MSW has been found to be well suited to the microbial degradation processes that are enhanced in an anaerobic bioreactor landfill based on the parameters listed above. "Several investigations confirm that the preferred substrates by methanogenic bacteria are easily degradable organic compound such as sugars, starches and products rich in cellulose and hemicellulose." These products account for "40-50% of household waste" (Binder, 2001). However, greenwaste diversion practices may reduce the amount of degradable material in the landfill, impacting bioreactor feasibility.

Although the chemical and biological characteristics of MSW make it a suitable candidate for disposal in an anaerobic bioreactor landfill, it is also heterogeneous by nature, which inhibits the distribution of liquid through the waste mass. If MSW is not homogenized prior to landfilling, a fraction of the waste is expected to be unaffected by the injected liquid and to degrade more slowly than the surrounding waste. Homogenization of the MSW prior to landfilling allows more even degradation and minimizes the potential for the development of preferential flow paths. Homogenization can be accomplished by mechanical pretreatment, such as separation and shredding, which is discussed in detail in Section 3.1. In addition, the process of compacting the waste during placement in the landfill allows for some level of homogenization, which in turn facilitate more complete waste degradation and minimizes preferential flow through the waste.

Site Climatic Conditions

Prior to selection of a site for development of an anaerobic bioreactor landfill, the climatic conditions and location of the site must be considered. Because of the dependence of the technology on a source for liquid (i.e., local water source and/or leachate generation), this technology may not be appropriate in arid climates.

Liquid for Injection

The most obvious choices for liquid injection to the landfill are water, leachate, or leachate (as available) supplemented by water. The introduction of water into the system, as opposed to leachate, may provide the added benefit of reducing contaminant load over time and reducing the potential for biological or physical clogging of the LCRS. However, “old leachates contain balanced populations of acidogenic and methanogenic bacteria which can inoculate the fresh material” (Binder, 2001) and increase the degradation rate.

In addition to water and leachate, various other choices for liquid injection may be considered on a site-specific basis. These include:

- gray water,
- bio-solids,
- septic waste,
- industrial waste,
- off-specification manufactured liquids (soda, beer, etc.),
- non-specified liquids, and
- dredged sediments.

Any alternative liquid considered for injection should be analyzed to verify that the composition of the liquid will not adversely affect the performance of the bioreactor. For instance, use of a high salinity liquid would suppress or kill the bacteria necessary for anaerobic degradation. Similarly, some liquids may react with the waste to produce undesirable by-products such as hydrogen sulfide or precipitates.

LCRS

The design of the LCRS should consider the increased flow expected, as well as the increased potential for physical and biological clogging due to the enhanced activity of bacteria within the waste mass. These factors may result in a change in LCRS design to reduce clogging potential or to provide a means for clearing fouled lines.

Waste Placement Procedures

Unlike the traditional MSW landfill, where waste is typically placed across a slope face that progresses across the lined area, waste in an anaerobic bioreactor is typically placed in horizontal layers. This allows several things to occur. First, rainfall over this larger area is allowed to infiltrate, enhancing degradation. Second, the horizontal surface provides a level surface for constructing injection/extraction piping. Third, the horizontal surface reduces the potential for vertical preferential flow paths in the waste.

Compaction procedures for the placement of waste should be evaluated on a site-specific basis depending on the characteristics of the waste and in conjunction with the design of the liquid injection system.

Daily Cover

The use of conventional daily cover comprised of finer grained soils creates horizontal layers of lower permeability and is not generally recommended in an anaerobic bioreactor for several reasons:

- it increases the potential for pore pressure generation in the waste between daily cover soil layers;
- it increases the potential for preferential flow through the waste mass; and
- it reduces the efficiency of gas extraction systems.

The use of temporary reusable daily cover, such as geomembranes, tarps, biodegradable films or alternative "permanent" daily cover with higher permeability, such as tire shreds, is often recommended with an anaerobic bioreactor landfill. However, low permeability daily cover may also have a beneficial impact on bioreactor operation by inducing lateral dispersion of the injected liquid within the waste mass.

4.1.3 Global Application of Technology and Case Histories

In addition to several European countries, Canada and the U.S. are beginning to accept anaerobic bioreactor technology as an alternative to "dry tomb" landfilling. Within the U.S. specifically, eight bioreactors have been identified, including one site in California. A summary of these sites is included in Table 4-A.

Table 4-A: Summary of Anaerobic Bioreactors in U.S. ***Source: Reinhart et al., 2002**

Location	Start Up Date	Leachate Injection Technique
Delaware Solid Waste Authority, DE	1982	Injection Wells, Surface Spray, Infiltration Ponds and Leach Fields
South West Landfill, FL	1990	Infiltration Ponds, Trenches (45 ft.)
Yolo County Landfill, CA*	1995	Injection Pits
Kootenai Co., ID*	1995	Surface Spray (Summer Only) Trenches (75 ft.)
Bluestem SWA, IA*	1998	Trenches (14 ft.)
Eau Claire, WI*	1998	Trenches (23 ft.)
Metro Landfill (Milwaukee), WI*	2000	Trenches (20-40 ft.)
Plantation Oaks, MS	2001	Trenches (55 ft.)

Most of these sites have been developed using trial-and-error methodology. The Delaware site is the oldest site in the U.S. and has undergone a series of changes in methodology and application since its inception in the early 1980s, especially with regard to the method of injection as shown in the above table. Most of the bioreactors developed subsequent to the Delaware site have utilized trench injection methods, which may be attributed to advances made and difficulties encountered at the Delaware sites which does not utilize trenches.

More recently, in the "Solid Waste Manager's Guide to the Bioreactor Landfill" prepared by SWANA (2002) it was reported that approximately 20 full-scale bioreactor demonstration projects are being conducted at sites across North America, including both anaerobic bioreactors and aerobic landfills. Four of these sites have been permitted under the USEPA's Project XL Program. This is a national pilot program that allows projects "to develop innovative strategies for achieving environmental and public health protection" (SWANA, 2002). A summary of information available on these four sites is included in Table 4-B.

Table 4-B: USEPA Project XL Bioreactor Sites **Source: SWANA, 2002**

Name/Location	Buncombe County Landfill Project Buncombe County, NC	Yolo County Central Landfill Davis, CA	Maplewood Recycling and Waste Disposal Facility Amelia County, VA	King George County Landfill and Rec. Ctr. King George County, VA
Owner	Buncombe County	Yolo County DPW	Waste Management, Inc.	Waste Management, Inc.
Disposal Rate (TPD)	320			
Landfill Size (Ac)	550	722		
Bioreactor Area (Ac)	23	20	10	10
Total Cells	10			
Bioreactor Cells	1	4	1	1
Bioreactor Technology	Anaerobic	Anaerobic (9.5 Ac) Aerobic (2.5 Ac)	Anaerobic	Anaerobic
USEPA XL Project	Yes	Yes	Yes	Yes
Project Goals	Demonstrate bioreactor landfill technology at full-scale (entire site)	Comparison of aerobic and anaerobic bioreactor approaches	Demonstrate recirculation of liquids (primarily leachate)	Demonstrate recirculation of non-hazardous liquid waste or stormwater
Bioreactor Water Sources	Leachate; river water.	Leachate; liquid waste.	Leachate; site liquids	Leachate; liquid waste
Leachate Recirculation Method	Horizontal trenches	Horizontal pipes		
Liner Type	Alternative Sub. D Liner	Alternative Sub. D Liner	Alternative Synthetic Liner	Alternative Synthetic Liner
Alternative Daily Cover	No	Shredded green waste; tarps	No	No
Biosolids Waste Augmentation	No	No	No	No
Waste Preprocessing	No	No	No	No
Const.	2001	2001		
Startup	2003	Spring 2002		
Operational Period for Data Collection	2003-2028	7/02 – 7/04		

Of particular interest to the application of bioreactor technology within California is the "Yolo County Controlled Landfill Demonstration" project (Augenstein et al, 1999). At this site, two test cells were developed (100 ft. x 100 ft. x 40 ft.) in the 1990s to compare experiences with an anaerobic bioreactor landfill with a typical MSW landfill. The bioreactor design and landfilling procedures adopted for the Yolo County bioreactor test cells are presented in Table 4-C.

Table 4-C: Yolo County Controlled Landfill Demonstration
Bioreactor Test Cell Design and Operational Features of Test Cells
Source: Augenstein et al., 1999

Component	Procedure
LCRS	1. Design with appropriate highly permeable bottom layer drainage to minimize leachate static head. With liquids addition, clogging can be avoided. For the Yolo demonstration, a 1-foot layer of pea gravel has been used.
Waste Placement & Daily Cover	2. Place waste largely following standard "conventional" landfill practice except permeable daily cover (chopped yard waste, soluble foam etc.) serves the daily cover function, rather than soil. This allows liquid permeation into waste at high rates and also limits lateral moisture diversion. The outer perimeter of lifts may also be sloped back in toward the landfill center to limit lateral I liquid seeps.
Gas Collection System & Liquid Injection System	3. Over the top lift of waste place sufficient permeable porous material (waste tire chips, gravel, etc) to form a highly conductive gas collection layer to capture and conduct gas to collection point. Provide for uniform liquid addition through multiple injections points by an injection piping system at the surface of the waste. (Control at Yolo is by a manifold of hoses with orifices) .
Final Cover	4. Cover waste with impermeable membrane and other necessary structural components.
Liquid Injection	5. Apply liquid (generally, leachate and water; possibly treated gray waters.) through injection piping. Liquid addition and waste moisture content can be managed as needed to preclude base hydrostatic head. Safety factors can be afforded in at least two respects: (a) elementary hydraulic analysis indicates liquid would not exit waste faster than it enters, and addition occurs slowly over several months. (b) Base leachate collection layer can easily be, and will be, conservatively designed so it could handle several-fold the anticipated flow while still avoiding any significant hydrostatic head (federal limits 30cm = 1ft.). Liquid injection was ceased in 1998 after two years of injection.
Gas Collection	6. Collect gas as it is generated. Size collection lines and other equipment to allow for greater gas recovery. Where economics are favorable, methane may be used for energy.

In conjunction with the Yolo County bioreactor test cell demonstration, instrumentation has been installed. Parameters that have been monitored include moisture, temperature, volume reduction, leachate flow and composition, and flow and composition of recovered gas. Of particular interest is the result of the temperature monitoring, which has shown an early increase in temperature, likely caused by the aerobic degradation of green waste within the waste mass. These increased temperatures (40-55º C) are very close to the optimum temperature for methane generation (Augenstein et al., 1999).

The results of liquid injection at Yolo County have in general been positive, as reported by Augenstein et al., 1999. "At the outset the timed surface liquid addition posed some uncertainties. For example channeling…and bypassing of waste elements could lessen effectiveness of additions. Fortunately, results to date [as of 1999] have been highly encouraging as to effectiveness of surface addition. The moisture sensor readings indicated well over 90% of the enhanced cell waste to be wetted (at all levels) within 6 months after start of liquid addition. While some channeling did occur (evidenced by outflow) most liquid was absorbed on the first pass. The outflow (channeled) liquid amounted to 5-30% of the addition rate over the 2-month interval of highest-rate well water addition. Recirculation and re-introduction of leachate ultimately led to essentially complete sorption of liquid and complete wetting of the waste as indicated by sensors."

It should also be noted that gas generation from the Yolo County bioreactor test cell was not reported to have decreased after liquid injection was stopped in 1998. Monitoring of the Yolo County Controlled Landfill Demonstration project is ongoing.

Through its participation in the USEPA Project XL Program, Yolo County is expanding its bioreactor demonstration to include a 12-acre landfill module, 9.5-acres of which will be designed as an anaerobic bioreactor. Horizontal leachate and water recirculation wells will be used and gas collection wells will be constructed. The 12-acre demonstration will be operated for two years (reportedly from 2000 through the end of 2002), and the results will be used to design the next phase of the demonstration project (SWANA, 2002).

4.1.4 Research Studies

Numerous studies have been performed or are ongoing to evaluate the performance and characteristics of anaerobic bioreactor landfill technology. In particular areas of research that have been studied to date include, but are not limited to:

- landfill gas production rates;
- water balance effects on biodegradation;
- anaerobic digestion and biodegradation rates;
- temperature effects on waste degradation;
- nutrient content of leachate; and
- management of nitrogen in leachate.

In addition, numerous lab-scale and field-scale studies are being performed to evaluate more closely the processes of anaerobic digestion, the effects of individual components on bioreactor performance, and the effects of bioreactor technology on the environment.

As suggested by Binder (2001), future research may focus on microbial activity under anaerobic conditions in order to clarify what are the limiting factors to waste degradation and to optimize bioreactor design. However, given the breadth of research that has been performed to date to investigate bioreactor performance, as well as the number of field-scale tests that have been performed, this technology may be considered field-ready for application at appropriate sites.

The widespread interest in anaerobic bioreactor technology had been demonstrated by the compilation of a "Solid Waste Manager's Guide to the Bioreactor Landfill" by SWANA (2002). This guide provides a source of current information regarding bioreactor implementation and discusses management-related issues.

4.1.5 Technologies in Combination

Due to the inherent heterogeneity of MSW, which can limit the effectiveness of **anaerobic bioreactor landfills** and **leachate recirculation systems**, it has been suggested that MSW be **mechanically pre-processed** prior to disposal in a bioreactor. This practice has not yet been implemented in the U.S., but results of studies in Europe (Binder, 2001) suggest that mechanical pre-processing of waste can provide positive results with respect to enhancing the rate of biodegradation in a bioreactor landfill and improving moisture distribution in a leachate recirculation system. Studies have shown that waste that has been bagged prior to disposal will not experience the same level of degradation as waste that has been removed from the plastic bags and shredded or milled.

Aerobic pre-treatment of waste prior to disposal in an **anaerobic bioreactor landfill** allows for accelerated degradation of the waste mass and a shorter stabilization period after the waste has been landfilled (Reinhart, 2000).

Anaerobic bioreactor landfills [as well as **leachate recirculation systems**] have been successfully implemented in combination with **air injection**, creating an **aerobic landfill** condition (Reinhart, 2000). The use of these technologies in combination allows for rapid aerobic degradation near the air injection system, as well as reduced biogas generation, with enhanced anaerobic degradation occurring elsewhere. Air injection systems may be distributed throughout the waste mass during construction or installed near the surface of the waste mass at the end of construction.

Delayed closure of a landfill may be particularly applicable if the landfill incorporates a technology for enhanced degradation prior to closure, such as an **anaerobic bioreactor landfill** or an **aerobic/semi-aerobic landfill**. By delaying closure, the waste mass is allowed to continue to degrade and stabilize, without excessive settlement of the final cover or accumulation of landfill gas below the cover system.

4.1.6 Application in California

Anaerobic technology is most advantageous with wastes with high organic content and requires relatively large quantities of liquid (generally water). Applicability must be evaluated on a site-specific basis considering the composition of waste entering the site and local climate characteristics and water supply. Diversion of green wastes, as practiced by most communities in California to meet AB 989 waste diversion mandates may limit some of the potential benefits of this technology, e.g., enhanced revenue from landfill gas-to-energy projects.

Due to the need for an ample liquid supply source, typically in the form of water or leachate, this technology may not be applicable in arid environments. In semi-arid conditions, a feasible alternative may be the construction of a single anaerobic bioreactor cell which is operated in tandem with traditional landfill cells, using leachate from all cells combined with surface water runoff as the liquid for injection in the bioreactor cell.

It is the USEPA's policy that additional liquid may only be added in single-lined landfills with Subtitle D prescriptive liner systems, limiting the applicability to Subtitle D compliant landfills that employ prescriptive liners. In other words, anaerobic bioreactor systems have only been approved for sites incorporating a compacted clay liner into the single composite liner system. Bioreactors have not been approved by USEPA for sites with a geosynthetic clay liner in lieu of compacted clay. USEPA's rationale for this restriction is unclear, as USEPA-funded liner performance field studies indicate that composite liners employing geosynthetic clay liners are at least as effective, if not more so, at liquid containment as composite liners employing compacted clay (USEPA, 2002a). Many, if not most, California landfill cells constructed in the past 5 years have employed geosynthetic clay liners, particularly on their side slopes, due to limited clay availability, constructability considerations, and cost. Therefore, at the present time, sites without a source for clay or with steep side slopes may be restricted from developing an anaerobic bioreactor unless a double liner is employed.

Current federal regulations further restrict recirculation to leachate that originates within the landfill, though a recent interpretation of an existing rule expanded this to include water from non-contaminated sources (Reinhart, 2000). The restriction on recirculation of leachate from other cells may be a barrier to the one bioreactor cell in a multi-cell landfill concept.

Existing waste management regulations require the application of a final cover system within 180 days of the closure of the landfill. Depending on the details of the individual bioreactor design, the enforcement of this regulation may limit optimization of the bioreactor system unless leachate and “make-up” water may continue to be injected beneath the final cover.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study identifies the following landfills as having planned or implemented anaerobic bioreactors:

- San Onofre Landfill (proposed);
- Yolo County Central Landfill; and
- Las Pulgas Landfill (proposed).

4.1.7 Evaluation of Benefits and Barriers

The potential benefits of implementing anaerobic bioreactor landfill technology, in comparison with conventional MSW landfilling techniques, can be summarized as follows (Levin, 2000; Jones et al., 2000; Hater et al., 2001):

Environmental Protection

- improved leachate quality with time in conjunction with stabilization of the waste mass;
- decrease in long-term environmental risk due to accelerated stabilization of the waste mass;
- improved performance of the final cover system due to the accelerated stabilization of waste;

Economic Effects

- reduced post-closure maintenance and potential for shortened length of the monitoring period with subsequent savings in post-closure costs;
- increased revenue from the sale of landfill gas as an energy source, or reduced costs from the onsite use of landfill gas as an energy source;
- increased air space due to enhanced degradation of waste and settlement;
- increased potential for revenue from new liquid waste streams if applied as an alternative liquid for injection; and
- lower leachate treatment and disposal costs, assuming leachate is injected.

The potential for barriers that may impact the successful implementation of anaerobic bioreactor landfill technology can be summarized as follows:

Environmental Protection

- increased potential for problems associated with internal and global stability if the landfill if not properly designed;
- increased dependence on LCRS, liner system and gas collection system performance in the short-term to minimize emissions to the environment;

Economic Effects

- increased complication and associated cost of design;
- increased up-front construction costs associated with the liquid injection and gas extraction systems;
- increased operational costs due to more complex systems; and

Other Issues

- technology may not be applicable to all sites, based on availability of liquid, site climatic conditions and waste characteristics.

4.2 Aerobic/Semi-Aerobic Landfill

4.2.1 General Description

The governing principle of aerobic / semi-aerobic landfill technology is that the introduction of air into the landfill induces aerobic degradation of the waste. Depending on the moisture content of the waste, liquid may also be injected to enhance degradation (Barstar, 2002). The degradation of waste under aerobic conditions occurs more quickly than under anaerobic conditions in a typical landfill (or an anaerobic bioreactor landfill) and produces carbon dioxide gas rather than methane as a byproduct. Aerobic degradation also results in enhanced stabilization of the waste mass prior to closure of the landfill.

Air may be introduced into the waste mass by means of 1) passive aeration, in which the waste mass is passively vented, air is drawn into the landfill by thermal convection under ambient conditions, and a semi-aerobic condition develops, or 2) air injection, in which air is applied under pressure to the waste mass and an aerobic condition develops. Passive aeration or air injection may be used in the design of a new landfill / landfill cell or in the remediation of an existing landfill / landfill cell. Similar methods of aeration may be used for both new and existing landfills.

Existing documentation on aerobic and semi-aerobic landfill technology and case histories of sites worldwide suggest that these technologies are more often applied to the remediation of existing landfills. Therefore, a detailed discussion of the application of aerobic / semi-aerobic landfill technology is included in Section 5, Remediation of Existing Landfills, of this report. Section 5.3 discusses the application of active aeration using methods of air injection. Section 5.2 discusses passive aeration.

4.2.2 Global Application of Technology and Case Histories

Three sites in the U.S. have been identified at which full-scale pilot tests on the application of aerobic landfill technology (e.g., air injection) in new landfill cells have been performed:

- Columbia County Baker Place Road Landfill near Augusta, Georgia;
- Live Oak Landfill near Atlanta, Georgia; and
- New River Landfill near Gainesville, Florida (Hudgins, 1999).

At the Live Oak Landfill, a pilot cell was developed using aerobic bioreactor landfill technology through air injection in conjunction with landfill mining for resource recovery. However, due to the high cost associated with the operation of the aerobic bioreactor and the landfill mining process as well as the low quality of the recovered material, it is our understanding that the project has been suspended.

More recently, the conversion of an existing 11-acre portion of the Cumberland County Solid Waste Complex in New Jersey has been contracted (Barstar, 2002). The volume of this aerobic landfill will be much larger than previous applications, with an initial volume of 1.2 million cubic yards.

4.2.3 Research Studies

Areas of research pertinent to aerobic and semiaerobic landfills that have been or are currently being studied, as well as areas requiring additional research, are included in the discussion of passive aeration and air injection, in Sections 5.2.4 and 5.3.4, respectively.

4.2.4 Technologies in Combination

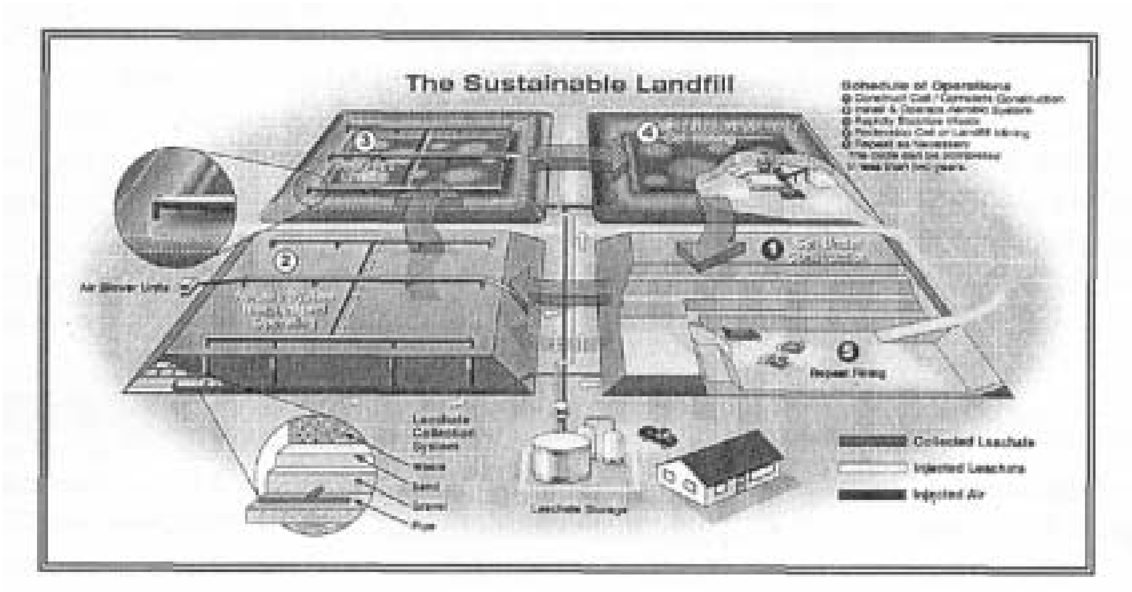
Delayed closure of a landfill may be particularly applicable if the landfill incorporates a technology for enhanced degradation prior to closure, such as an **anaerobic bioreactor landfill** or an **aerobic/semi-aerobic landfill**. By delaying closure, the waste mass is allowed to continue to degrade and stabilize, without excessive settlement of the final cover or accumulation of landfill gas below the cover system.

A model for applying **landfill mining** technology in conjunction with an **aerobic landfill** has been proposed by Hudgins, 2001. This model consists of a four-cell "sustainable" landfill scheme, filled sequentially with each cell in a different phase of development, as shown in Figure 4.2.

This model allows for degradation of the MSW prior to mining and recovery of recyclable materials. The residual material may then be reused in the landfill as daily cover material.

Barstar reports that "While the construction and operational startup costs for the [sustainable] aerobic landfill may be significant, …the avoided costs for leachate pretreatment and leachate treatment and the recouped air space make the project economically attractive during the active life of the landfill, even before the reduced post-closure costs are considered" (Barstar, 2002). However, the cost effectiveness of aerobic landfills tends to be a widely contested issue.

Figure 4.2: The Sustainable Landfill **Source: Hudgins, 2001**



4.2.5 Application in California

Aerobic degradation within a landfill results in an increase in landfill temperature and thus an increased susceptibility to landfill fires. Because moisture can work to lower the in-situ temperature of the waste mass, the control of the in-situ moisture content of the waste is critical to the application of aerobic / semi-aerobic landfill technology. The in-situ moisture content of the waste is primarily a function of waste type and site climatic conditions, and should be considered on a case-by-case basis for implementation in California.

Semi-aerobic landfill technology utilizing passive aeration has been implemented in Japan and other Asian countries, primarily in areas where heavy rains increase the moisture content of the waste. This technology has not yet been tried in North America or Europe. It may have applicability to areas in northern California where climate conditions are somewhat similar to parts of Japan.

Aerobic landfill technology utilizing air injection has been implemented at multiple sites in the U.S. and Europe, usually in conjunction with liquid or leachate injection to control the moisture content of the waste. One barrier to implementation of this technology may be the tendency of some regulators to consider the high temperatures that accompany aerobic decomposition (sometimes on the order of 160 to 180 F) to be indicative of a landfill fire.

According to Barstar (2002), aerobic landfills “are more operationally intense than anaerobic bioreactor landfills during their operation. [It has been]… determined that the additional power required to inject air into an aerobic bioreactor was twelve times higher than the power required to extract LFG in an anaerobic bioreactor. However, post-closure costs should be substantially reduced because of reductions in LFG generation and cover settlement and leachate treatment costs.”

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study does not identify any landfill sites in California that have planned or implemented aerobic or semi-aerobic landfill cells.

4.2.6 Evaluation of Benefits and Barriers

The potential benefits of implementing aerobic/semi-aerobic technology, in comparison with conventional MSW landfilling techniques, can be summarized as follows:

Environmental Protection

- reduced generation of methane due to aerobic degradation of waste;
- improved performance of the final cover system following closure;
- decrease in long-term environmental risk due to accelerated stabilization of the waste mass;
- a potential for improved leachate quality due to a reduction of VOCs in operating landfills;

Economic Effects

- low operations and maintenance costs, since passive aeration incorporates no mechanical systems;
- increased air space due to enhanced degradation of waste;
- system optimization may allow costs to be minimized;
- shortened post-closure maintenance and monitoring period;
- wider options for site-reuse following closure due to accelerated stabilization of waste;

Other Issues

- requires no changes to Subtitle D landfill regulations; and
- reduced landfill odor due to aerobic degradation of waste.

The potential for barriers that may impact the successful implementation of passive aeration technology can be summarized as follows:

Environmental Protection

- insufficient moisture in the waste mass may result in high temperatures and landfill fires if moisture is not properly monitored and controlled;
- improper monitoring and mixing of oxygen and methane may result in an explosive environment within an aerobic landfill;
- LCRS in semi-aerobic landfill may be susceptible to biological clogging, reducing the ability to control head on the liner;

Economic Effects

- both aerobic and semi-aerobic landfills require an upfront capital cost expenditure to design and construct the system;
- aerobic landfill requires high operational cost expenditure (energy costs for air injection) when compared to other landfill design and remediation technologies (i.e., anaerobic bioreactor);

Other Issues

- technology may not be applicable to all sites, based on site climate, moisture characteristics of waste, organic content of waste, waste density, and configuration and capacity of existing LCRS;
- semi-aerobic landfill technology is untried in areas where waste characteristics and climatic conditions are similar to expected conditions in California; and
- potential for aesthetic issues due uncontrolled odor releases from landfill "blow-outs" (excessive air injection).

4.3 Alternative Base Containment Systems

Current California regulations require construction of a Subtitle D base containment system at all proposed units of MSW landfills to minimize the adverse effects of waste disposal on the environment. The prescriptive base liner system consists of the following components.

- a composite barrier, consisting of a compacted clay liner at least two feet thick with a saturated hydraulic conductivity less than or equal to 1×10^{-7} cm/s overlain by a synthetic geomembrane at least 40-mils thick (or 60-mils if high density polyethylene); and
- a leachate collection system.

In addition, an underdrain system may be required as part of the base containment system if the separation between groundwater and the liner system is expected to be less than 5 ft.

Alternatives to the prescriptive liner system may be approved if it can be shown that the alternative system satisfies the regulatory engineering and performance criteria. Some alternatives, such as a GCL composite liner system, have gained widespread acceptance, and would no longer be considered "emerging technologies." Other alternatives and enhancements to the prescriptive liner system are gaining acceptance. The following alternatives and enhancements to the prescriptive base containment system will be discussed briefly as part of this study:

- double liner systems;
- electrically-conductive liners;
- white liners;
- tensioned or shaded liners;
- encapsulated geosynthetic liners; and
- inward gradient landfills.

4.3.1 General Descriptions

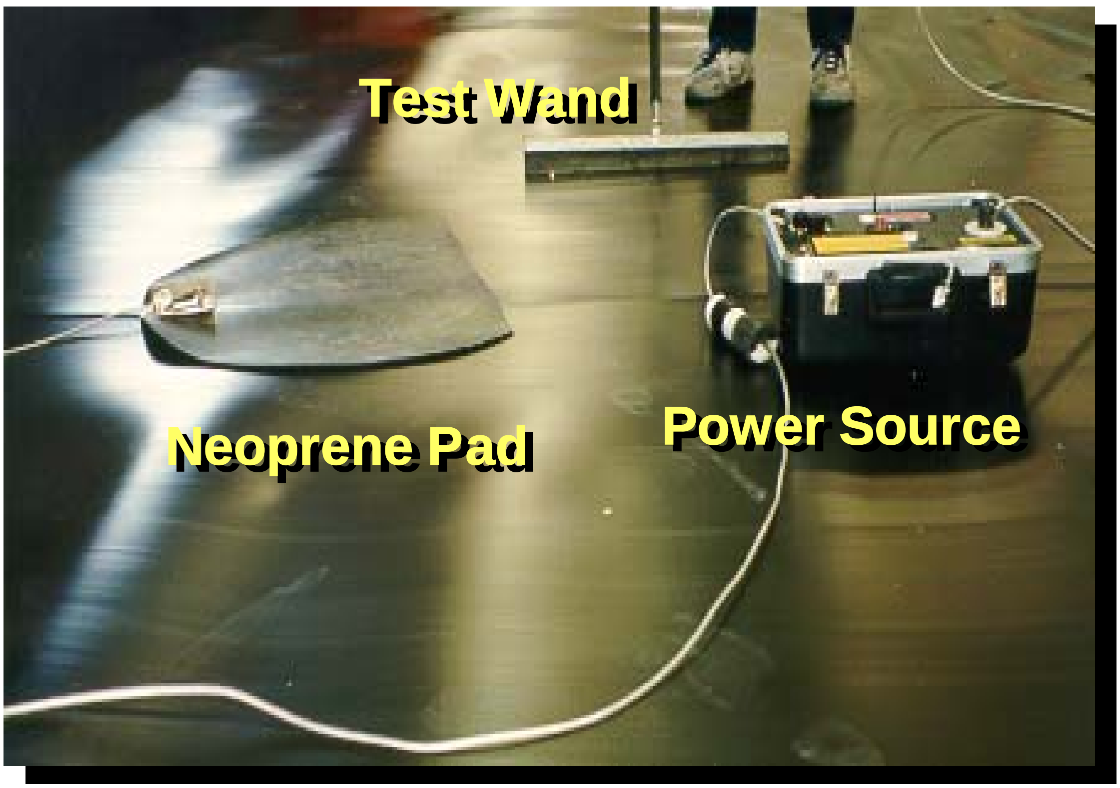
4.3.1.1 Double Liner Systems

Double liner systems, in particular double composite liner systems, are recognized as providing an even higher level of containment than prescriptive Subtitle D single composite liner systems. However, double composite base liner systems are also significantly more expensive to construct than a single composite system. Therefore, the question becomes whether the additional containment capacity of a double liner composite system is necessary to protect the environment. In regards to the environmental protection provided by single composite liners, a recent USEPA study on field performance of liner systems (approved for publication) found that “prescriptive minimum criteria Subtitle D [single composite] liner systems can achieve a very high hydraulic efficiency and are capable of preventing adverse impacts to groundwater” (USEPA, 2002a)

4.3.1.2 Electrically-Conductive Liners

The use electrically conductive geomembrane provides a means for identifying holes and leaks during construction. The geomembrane incorporates a conductive layer co-extruded on the underside of the liner. This layer consists of high-purity carbon black, between 3 and 5 mils thick. To test for holes and leaks, a charge is applied to the conductive layer after installation and a conductive wand is swept across the surface of the liner. In this method, called “spark testing”, a spark will be generated between the liner and the wand anywhere a hole is encountered. The equipment used during installation of an electrically-conductive liner are shown in Figure 4.3.

Figure 4.3: Electrically-Conductive Liner **Source: Thiel et al., 2001**



The effectiveness and applicability of conductive liners has, however, been found to be limited. The system may not identify small holes or leaks in the liner. The surface of the liner must be dry during testing. Conductive liners are not applicable for use with encapsulated GCLs or with double- sided textured geomembrane.

4.3.1.3 White Liners

Typically, the geomembrane component of the prescriptive base containment system is black. However, a geomembrane with a white surface can be manufactured at a small additional cost by co-extrusion of HDPE geomembrane with white pigment along with the convention black geomembrane. White liner may be substituted for black liner to control wrinkles and reduce surface temperatures during construction. Use of white liner results in a larger quantity of smaller wrinkles than black liner, which simplifies wrinkle management during construction. Using white liner instead of black liner also reduces surface temperature on the geomembrane, making liner installation in hot climates easier. In addition, the use of white liner may facilitate construction quality assurance (CQA). With white liner it is obvious if the edge of a liner has not been adequately ground prior to seaming. White liner is being used more and more frequently, and typically costs between 3 and 5 cents more per square foot than black geomembrane.

4.3.1.4 Tensioned or Shaded Liners

In German practice, liners are sometimes tensioned and/or shaded from sunlight to control wrinkles, as shown below While this practice can essentially eliminate wrinkles, it can greatly complicates installation and increase installation cost. The general consensus in the United States is that wrinkling is not a significant enough problem to warrant this expense.

Figure 4.4: Tensioned-Liner Installation and Protective Structure Source: Thiel et al, 2001

4.3.1.5 Encapsulated Geosynthetic Clay Liners

Encapsulation of a geosynthetic clay liner (GCL) between two geomembranes has been suggested as a means of enhancing the shear strength of the GCL by slowing or preventing hydration. This technique has been employed for the side slope liner system of several California landfills. Typically, the upper geomembrane seams are welded using conventional geomembrane liner seaming techniques while the lower geomembrane may be seamed either by simply lapping the seams or by welding. Numerical analysis (Giroud, et al., 2002) indicates that it may take thousands of years for as much as 25 percent of the GCL to hydrate when seams are simply lapped. For welded seams, the anticipated hydration is very small. According to Thiel, et al. (2001), the lower geomembrane may also reduce the leakage rate through typical liner defects by several orders of magnitude.

4.3.1.6 Inward Gradient Landfills

For sites with high groundwater, one alternative base containment system that may be applicable is the inward gradient landfill, also called a hydraulic containment landfill. The premise behind an inward gradient landfill is that by constructing the landfill cell below the surrounding groundwater table and providing a higher conductivity flow path groundwater is directed inward toward the waste at a rate that exceeds the outward chemical diffusion rate from the waste, thereby protecting the surrounding environment from leachate contamination.

Theoretically, this concept of hydraulic containment would be applicable to landfills without a base containment system. However, the regulatory framework in the U.S precludes construction of a new landfill without a base containment system. The inward gradient concept may be applied in conjunction with a base containment system in the following configurations:

- a prescriptive single composite liner system (geomembrane over compacted clay), with an underdrain system below the liner to provide a high conductivity flow path for groundwater;
- an alternative single composite liner system (geomembrane over GCL) underlain by a compacted soil separation layer and an underdrain system; or
- a double lined system with no geomembrane in the lower liner and a high conductivity leachate detection (and groundwater collection) system between the two liners.

The inward gradient concept is not compatible with a prescriptive single composite liner without an underdrain, because the geomembrane component of the composite liner is expected to have a considerably lower hydraulic conductivity that the surrounding soil formation, restricting inward flow.

4.3.2 Global Application and Case History

4.3.2.1 Double Liner Systems

Double liner systems are required in some states, including New York and Pennsylvania, for all MSW Subtitle D landfills. In other states they are required only when the landfill site meets certain geologic criteria, as in Delaware and New Jersey. In California, double liner systems are only required for Class I (Hazardous waste - Subtitle C) facilities, but have recently been employed at one Class II facility, the Fink Road landfill in the Central Valley Water Board region, in response to concerns raised by the Central Valley Regional Water Quality Control Board (CVRWQCB) about single composite liners. It should, however be recognized that Class II landfills are Subtitle D landfills per federal regulations, but differ from Class III Subtitle D landfills in California.

4.3.2.2 Electrically-Conductive Liners

Electrically-conductive geomembrane liners have been used in numerous applications in the US and worldwide. Electrical leak detection systems composed of a grid of fine wires placed beneath the membrane (an alternative to electrically conductive sheet), have recently been employed at three Central Valley landfills in response to concerns from the CVRWQCB about single composite liners. They have been employed at Bakersfield Metropolitan Sanitary Landfill and Shafter-Wasco Sanitary Landfill in Kern County. The CVRWQCB has accepted this "enhanced CQA" as an alternative to double liners or additional clay beneath a single composite GCL liner.

4.3.2.3 White Liners

White liner has been used in numerous applications in US and worldwide. Most recently it was installed at Los Reales Landfill in Tucson, Arizona.

4.3.2.4 Tensioned or Shaded Liners

Tension and shaded liners have been used widely in Germany. However no site have been identified in North America where this technology has been employed.

4.3.2.5 Encapsulated Geosynthetic Clay Liners

Encapsulated GCLs have been used at several landfills in California, including Sonoma County's Central Landfill, Bakersfield Metropolitan Sanitary Landfill in Kern County, and Shafter-Wasco Landfill in Kern County.

4.3.2.6 Inward Gradient Landfills

Inward gradient landfills have been applied extensively in Canada, but have not gained widespread acceptance in the United States as a method of protecting the environment. Existing California regulations require a 5 ft. minimum separation of the liner system from surrounding groundwater, precluding the application of an inward gradient landfill without special approval.

Inward gradient landfill technology has been applied at the Gray Wolf Regional Landfill in Dewey, Arizona. In Cell 4 at this site, the base liner system was installed up to 15 feet below the groundwater table. A geocomposite underdrain was installed below a single composite liner consisting of a 60-mil geomembrane overlying a GCL overlying a 2-ft. compacted soil layer. The high conductivity geocomposite layer redirects groundwater flow toward the landfill on all sides, and into the underdrain system. The anticipated groundwater inflow rate in Cell 4 is 15 liters per minute, based on a hydrogeologic study of the site (Verwiel, 2001).

Groundwater collected in the underdrain is currently discharged into an onsite surface water pond. When build-out of the site is complete, collected groundwater will flow into a sump, where samples will be collected for testing and where the groundwater will be retained for re-use onsite.

4.3.3 Research Studies

Very little existing or ongoing research on the applicability and effects of alternative base containment systems has been identified during this study. Industry publications for the application of these base containment technologies were the primary sources for the development of this discussion, as well as a review of experiences at a few sites. To fully evaluate the suitability of one of the alternative base containment systems considered in this study for application at a particular site, further evaluation of experiences at existing sites is recommended.

4.3.4 Technologies in Combination

No potential for added benefit from applying alternative base containment systems in combination with the other technologies discussed in this report have been identified. However, **electrically-conductive geomembrane liners** are not applicable for use with **encapsulated GCLs.**

4.3.5 Application in California

The performance of Subtitle D prescriptive single composite liner systems and the ability of such systems to adequately protect the environment has been questioned by some environmental activists. California's Central Valley Regional Water Quality Control Board currently requires a demonstration that the proposed liner system will meet California water quality objectives prior to approval of any liner system, prescriptive or alternative. This liner performance demonstration must include cost and performance comparisons with double and triple liner systems if a single composite liner system is proposed. However, recent USEPA field studies of liner system performance (USEPA, 2002a) indicate that the regulatory minimum single composite liner system is "capable of preventing adverse impacts to groundwater" under virtually all circumstances.

Experience with the field performance of single composite liner systems (USEPA, 2002a) indicates that liner leakage rates will be very small for MSW landfills with a single-composite liner system properly designed and constructed to minimum state and federal criteria with good CQA practices. These small amounts of leakage can generally be absorbed by a CCL liner component and unsaturated foundation soils without adverse environmental impact. Leachate constituents can also be attenuated by adsorption, biodegradation, and other mechanisms. Experience with the fate and transport of leachate constituents indicates that, for the level of leakage anticipated at typical MSW landfills, there should be no impact to groundwater at the downgradient landfill boundary. USEPA's recently completed study of problems at modern landfills supports this finding: groundwater contamination resulting from leakage through a composite liner was not identified at any of the more than 100 landfills in the study (Gross et al., 2002). Therefore, enhancements to the prescriptive single composite liner system, e.g., double liners, should only be necessary for MSW landfill sites in California with exceptional conditions. This may include sites with significant karst geological features, sites over sole source aquifers without geological barriers beneath the waste unit, or sites where groundwater cannot be monitored.

Encapsulation of the geosynthetic clay liner (GCL) can significantly increase the shear strength of the GCL. This can be of particular importance with respect to canyon landfills, where use of a GCL is necessary because the construction of a low permeability soil liner is either cost-prohibitive or technically infeasible. Without the increased shear strength provided by encapsulation, considerable capacity may have to be sacrificed and/or operational efficiency may be compromised. Encapsulated GCLs have already been used at over a half-dozen landfills in California.

The implementation of an inward gradient landfill without construction of a base liner system, as has been implemented at sites in Canada, is precluded by state and federal regulations. However, when constructed in conjunction with the liner configurations described in Section 4.3.1.6, inward gradient landfill technology may be applicable to sites in California with high groundwater conditions. Current California regulations that require a 5 ft separation between groundwater and waste would seem to preclude construction of an inward gradient landfill in California at this time.

The cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study identifies the following landfills where alternative base containment system have been planned or implemented:

- Azusa Land Reclamation Company Landfill (double liner system);
- CWMI Kettleman Hills Facility (double liner system);
- Rock Creek Solid Waste Facility (double liner system); and
- Woodville Disposal Site (white geomembrane).

4.3.6 Evaluation of Benefits and Barriers

4.3.6.1 Double Liner Systems

The potential benefits of implementing a double liner system, in comparison with a prescriptive Subtitle D single composite liner system, can be summarized as follows:

Environmental Protection

- provides a higher level of containment than prescriptive Subtitle D single composite liner systems.

The potential for barriers that may impact the successful implementation of a double liner system can be summarized as follows:

Economic Effects

- considerably more expensive to install than a prescriptive Subtitle D single composite liner system.

4.3.6.2 Electrically-Conductive Liners

The potential benefits of using an electrically-conductive geomembrane liner as a component of a single composite liner system, can be summarized as follows:

Environmental Protection

- holes or leaks in the geomembrane component may be more easily identified during construction than using a conventional geomembrane component, creating the potential for a higher level of containment.

The potential for barriers that may impact the successful utilization of an electrically-conductive geomembrane liner can be summarized as follows:

Environmental Protection

- effectiveness and applicability may be limited;
- small holes or leaks in the liner may not be identified;

Economic Effects

- more expensive than non-conductive geomembrane

Other Issues

- the surface of the liner must be dry during testing;
- not applicable for use with encapsulated GCLs; and
- not applicable with double- sided textured geomembrane.

4.3.6.3 White Liners

The potential benefits of using a white geomembrane liner as a component of a single composite liner system, can be summarized as follows:

Environmental Protection

- by making proper grinding more identifiable, improper seams may be more readily identified during construction;

Economic Effects

- product is readily available;

Other Issues

- controls wrinkles during construction; and
- reduce surface temperatures during construction, facilitating use in hot climates.

The potential for barriers that may impact the successful utilization of a white geomembrane liner can be summarized as follows:

Economic Effects

- approximately 3 to 5 cents per square foot more expensive than black geomembrane.

4.3.6.4 Tensioned or Shaded Liners

The potential benefits of using a tensioned or shaded geomembrane liner as a component of a single composite liner system, can be summarized as follows:

Other Issues

- controls wrinkles during construction.

The potential for barriers that may impact the successful utilization of a tensioned or shaded geomembrane liner can be summarized as follows:

Economic Effects

- considerably more expensive to install than a non-tensioned or non-shaded geomembrane; and

Other Issues

- complicates installation.

4.3.6.5 Encapsulated Geosynthetic Clay Liners

The potential benefits of using an encapsulated GCL as a component of a single composite liner system, can be summarized as follows:

Environmental Protection

- may enhance the shear strength of the GCL by slowing or preventing hydration; and
- has the potential to slow leakage through the liner system, when compared to a single composite liner system using a non-encapsulated GCL.

The potential for barriers that may impact the successful utilization of an encapsulated GCL can be summarized as follows:

Economic Effects

- considerably more expensive to install than a single composite liner system using a non-encapsulated GCL.

4.3.6.6 Inward Gradient Landfills

The potential benefits of implementing an inward gradient landfill instead of a prescriptive base containment system include the following (Bonaparte, 1995):

Environmental Protection

- potential for increased protection of the environment over prescriptive base liner for increased risks (technological, environmental, operational and system due to increased prevention of leakage out of the unit); and

Economic Effects

- provides reasoning for minimizing long-term maintenance of cover system and LCRS.

The potential for barriers that may impact the successful implementation of an inward gradient landfill can be summarized as follows:

Environmental Protection

- uncertainty associated with long-term groundwater conditions may result in a decreased environmental benefit with groundwater fluctuation;

Economic Effects

- potential for handling (and possibly treating) a large volume of liquid;

Other Issues

- technology may not be applicable to all sites, based on groundwater conditions and subsurface characteristics; and

- possible difficulty obtaining regulatory acceptance.

4.4 Alternative Cover Systems

Current California regulations require that construction of the final cover system begin within 30 days after the last wastes are received in the landfill and that the construction of that cover be completed within 180 days (unless an alternative schedule is approved with the final closure plan). The required components of the cover system vary depending on the classification of the landfill, but the prescriptive cover system generally consists of a low permeability barrier layer with a hydraulic conductivity less than that of the base liner system or underlying geologic material, and incorporates a foundation layer and a vegetative topsoil layer as shown in Figure 4.5.

The prescriptive cover barrier layer must consist of at least 1 ft (0.3 m) of low permeability soil with a saturated hydraulic conductivity no greater than $1x10^{-6}$ cm/s. Geomembranes and geosynthetic clay liners are generally accepted as engineered alternatives to this prescriptive barrier layer. The requirement that the hydraulic conductivity of the barrier layer be less that that of the base liner and underlying geologic material is generally interpreted as requiring a geomembrane barrier layer in the cover of any landfill with a geomembrane in the base liner system.

Regulations provide for alternative cover systems as long as they provide equivalent or superior protection of groundwater, a provision generally interpreted to mean the alternative cover must allow less liquid flow through the cover than the prescriptive cover. These requirements essentially halt the inflow of liquid into the landfill and significantly reduce the rate of degradation of waste within the landfill after construction of the cover.

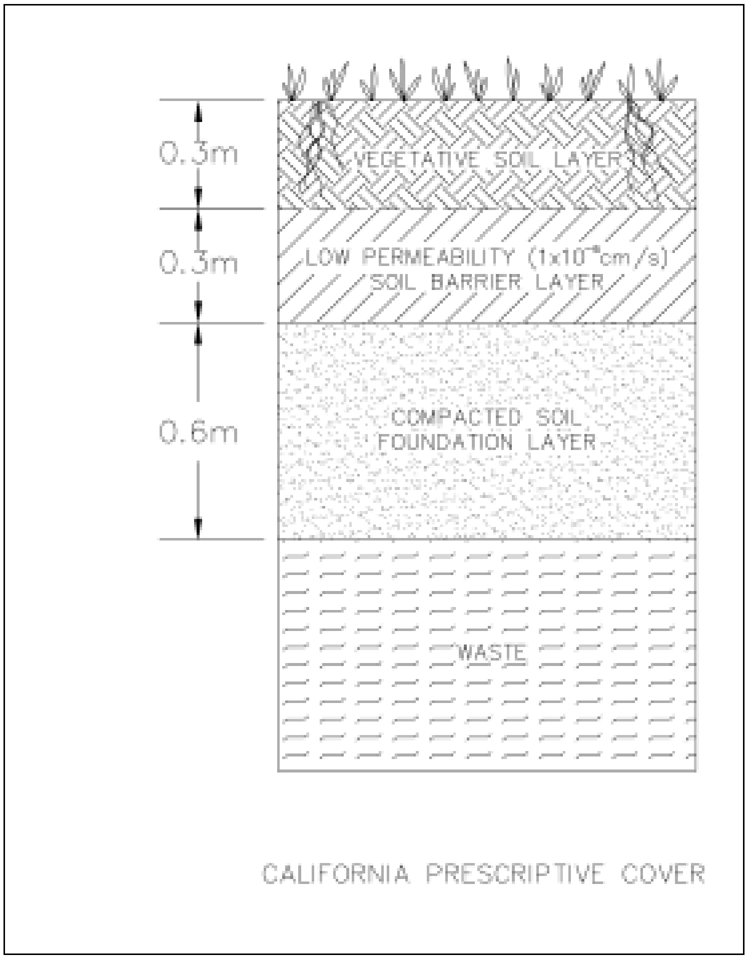
Since the early 1990’s the USEPA has recognized that the implementation of a final cover system shortly after the receipt of wastes has ended may not be appropriate for all sites, especially due to ongoing settlement of waste (USEPA, 1991). Furthermore, site-specific characteristics, including climate and vectors, such as burrowing animals, may also make the implementation of a prescriptive final cover system undesirable. Various alternatives to the prescriptive requirements for final closure of landfills have been proposed, including but not limited to the following:

- monolithic soil evapotranspirative cover system;
- capillary-break evapotranspirative cover systems;
- phytoremediation evapotranspirative cover systems;
- exposed geomembrane cover systems (EGCS); and
- delayed closure.

These five alternatives to the prescriptive final closure requirements will be considered in this study.

Figure 4.5: California Prescriptive Cover

Source: Kavazanjian, 2001



4.4.1 Monolithic Evapotranspirative Soil Cover System

4.4.1.1 General Description

The monolithic evapotranspirative (ET) soil cover is the most common alternative cover system installed in arid and semi-arid regions of the western United States. Over a dozen ET covers have been granted conditional approval in southern California. An ET cover relies on the storage capacity, evaporation and transpiration characteristics of the cover soil. Infiltrating surface water is stored in the cover soil during the wet periods and released to the atmosphere through evaporation and transpiration during the dry season.

An ET soil cover consists of a single, vegetated soil layer, typically between 4 and 6 ft. (1.2 to 1.8 m) thick. A typical cross-section of an ET cover is shown in Figure 4.6.

The cover soil is designed, as described below, so that it maintains an unsaturated state. Infiltration into the waste mass is limited because the unsaturated hydraulic conductivity of the silt and silty sand materials that comprise the cover soil can be up to several orders of magnitude lower than the saturated hydraulic conductivity of compacted clay barrier component of a prescriptive cover system.

4.4.1.2 Detailed Description and Process Options

For the design of an ET cover system, the following primary criteria should be considered:

- the required storage capacity of the cover soil;
- the evaporation potential of the soil and site; and
- transpiration characteristics of the storage layer and vegetation.

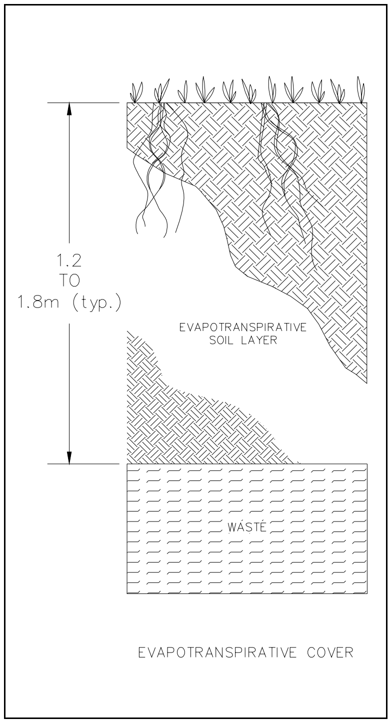
Capacity of the Cover Soil

To design the ET cover system to function properly, the water balance characteristics at the site must be considered to provide a cover soil that has sufficient capacity to store the volume of liquid that infiltrates without allowing seepage into waste during wet periods and sufficient evaporation and transpiration to restore the storage capacity during dry periods. In a properly functioning ET cover system the field capacity of the storage layer will not be exceeded. Water balance characteristics are defined by site precipitation and evaporation characteristics, surface vegetation coverage, and vegetative transpiration characteristics.

Evapotranspiration of the Cover Soil

The soil selected for the cover should have characteristics that balance evapotranspiration with storage capacity. To regain storage capacity after significant infiltration has occurred over a short period of time (i.e., during and after a heavy rain event), liquid in the cover soil should evaporate or transpire quickly enough that the moisture content of the cover soil does not increase steadily over time. This allows a steady-state moisture condition below the field capacity of the cover soil to be maintained.

Figure 4.6: Evapotranspirative Cover System **Source: Kavazanjian, 2001**



4.4.1.3 Global Application of Technology and Case Histories

The ET cover system is particularly applicable to arid and semi-arid climates, such as is found in parts of the southwestern United States. This technology has been employed at over a dozen sites in the southwest United States, some of which are listed in Table 4-D.

Table 4-D: Sites Using Monolithic Evapotranspirative Cover System

Site	Location
Azusa Landfill	Azusa, CA
Bishops Canyon Landfill	Los Angeles, CA
Bradley West	Sun Valley, CA
California Valley Landfill	San Luis Obispo County, CA
Del Rio Landfill	Phoenix, AZ
Kirtland Air Force Base	Albuquerque, NM
Lopez Canyon Landfill	Los Angeles, CA
Marine Corps Station, El Toro	El Toro, CA
Norton Air Force Base	San Bernardino, CA
Operating Industries, Inc. (OII) Landfill	Monterey Park, CA
Sunshine Canyon Landfill	Los Angeles, CA
Tajiguas Landfill	Santa Barbara County, CA
Yucaipa Landfill	Yucaipa, CA

However, it should be recognized that the portion of these sites that have received evapotranspirative covers may not have accepted MSW, and thus may not be directly comparable to other sites discussed in this study.

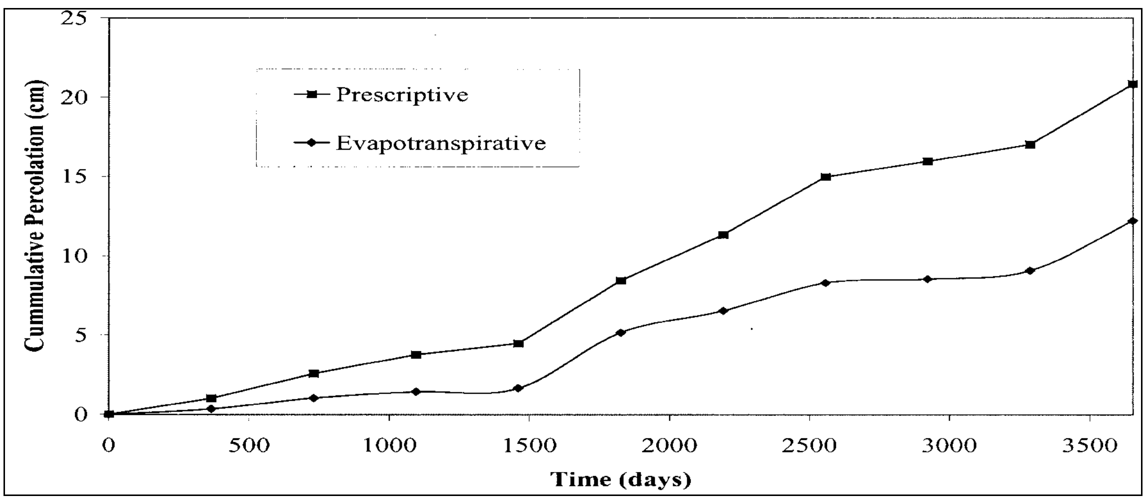
The ET cover system installed at the Yucaipa Landfill (listed above) is described in detail in Kavazanjian (2001). The following excerpt provides a description of the ET cover system implemented at the site, as well as the design procedures and regulatory approval process.

"The Yucaipa landfill is located in the City of Yucaipa in the San Bernardino Mountains in Southern California….The climate at the landfill site is semi-arid, with a mean annual rainfall of approximately 15 in. (380 mm)….The landfill accepted municipal solid waste from 1963 to 1980. However, formal closure design and construction activities did not take place until 1996-1997. In 1997, a monolithic soil ET final cover was constructed on the landfill using native soils. As a condition for approval of the cover, the Santa Ana Region California Regional Water Quality Control Board required performance monitoring of the alternative final cover."

"Water balance analyses conducted using LEACHM compared the performance of monolithic covers of various thickness to the performance of a California prescriptive cover with a vegetative cover layer composed on on-site soil and a barrier layer with a saturated hydraulic conductivity of 1 x 10-6 cm/s. Results of these analyses indicated that a 4-ft (1.2-m) thick ET monolithic cover composed of on-site soil with a saturated hydraulic conductivity of 1.5 x 10-5 cm/s offered superior percolation resistance compared to the prescriptive cover." Figure 4.7 compares the 10-year cumulative percolation of the monolithic soil and prescriptive covers as predicted by LEACHM.

Figure 4.7: Cumulative Percolation, Prescriptive and ET Covers, Yucaipa Landfill

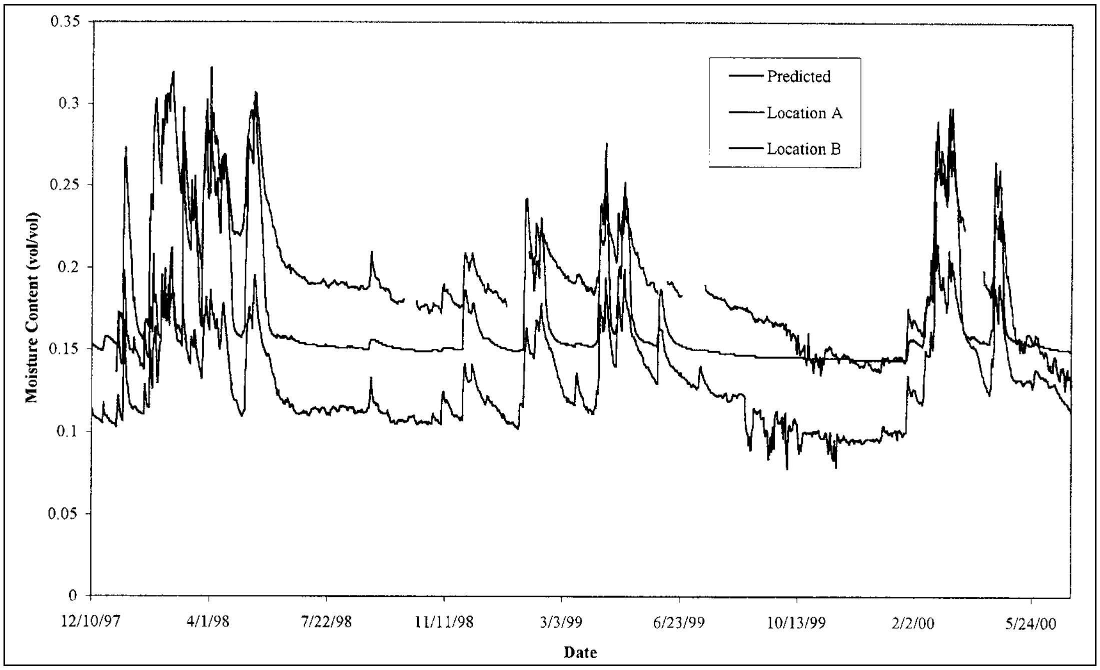
Source: Kavazanjian, 2001



"To monitor the ET monolithic cover, a weather station and two soil moisture monitoring stations were installed at the site in January 1998, following the completion of ET cover construction. At each soil moisture monitoring station, time-domain reflectometry (TDR) probes were configured to give a continuous profile of soil moisture content in the final cover to a depth of 6 ft (1.8 m). Figure 4.8 "shows a comparison between the observed seasonal moisture content fluctuation at the same depth at each TDR monitoring station and the moisture content fluctuation predicted at that depth by LEACHM using the climate data collected by the on-site weather station.

Figure 4.8: Observed and Predicted Soil Moisture Contents, Yucaipa Landfill

Source: Kavazanjian, 2001



"The data presented in [Figure 4.8]… was used to demonstrate to the regulators that the unsaturated flow model used to establish the superior percolation resistance of the ET cover compared to the prescriptive cover was reliable for predicting relative percolation through the ET and prescriptive covers. This data, combined with "conventional" landfill monitoring data for air quality, water quality, and vadose zone gas concentrations that indicate the final cover is performing satisfactorily, will be submitted at the end of the conditional approval monitoring period with a request for final approval of the ET cover."

4.4.1.4 Research Studies

Studies are being performed nationwide to evaluate the performance of a variety of alternative cover systems, including monolithic evapotranspirative soil cover systems. The following two studies are particularly applicable to California because they are evaluating the performance of landfill cover systems in arid and semi-arid environments.

- The Alternative Landfill Cover Demonstration (ALCD), sponsored by the Department of Energy, is a 5-year (minimum) study of the performance of six test cells (4 alternative cover systems and 2 prescriptive cover systems) constructed at a site near Albuquerque, New Mexico (USDOE, 2000).

- The Alternative Cover Assessment Program, sponsored by the USEPA, is establishing field demonstrations at 12 sites nationwide to evaluate the performance of various alternative cover systems over a five-year period. Currently test sections of evapotranspiration cover systems are being installed and monitored nationwide, including several in California (Bolen et al., 2001).

However, both of these studies are "in progress," so no definitive findings are available from them at this time.

4.4.1.5 Technologies in Combination

No potential for added benefit (or risk) from applying an evapotranspirative monolithic soil cover system in combination with the other technologies discussed in this report have been identified.

4.4.1.6 Application in California

In general, non-barrier cover systems, including monolithic evapotranspirative cover systems, have been developed with arid and semi-arid climates in mind, as are found in most parts of California. Studies are ongoing to evaluate the performance of these types of alternative cover systems in arid and semi-arid climates. These studies generally employ conditional approvals, wherein the owner is prohibited from withdrawing money from financial assurance funds until after several years of post-construction monitoring has been completed. While regulations that allow for engineered alternatives to the prescriptive cover system facilitate the application of alternative cover systems in California, long-term conditional approvals may dissuade some owners from employing alternative covers even in cases where it is recognized that the prescriptive cover (i.e., a clay barrier cover) will not perform satisfactorily. A list of sites in California where evapotranspirative cover systems have been employed is included in Table 4-D.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study identifies 22 landfills where monolithic soil covers have been proposed or implemented. However, the cross-media inventory does not specify whether these covers have been designed as monolithic evapotranspiration soil covers and thus are not listed here.

4.4.1.7 Evaluation of Benefits and Barriers

The potential benefits of implementing an ET cover system instead of a typical final cover system include the following:

Environmental Protection

- equivalent or superior isolation of waste and erosion resistance than the prescriptive cover system;
- superior resistance to cracking in arid / semi-arid climates over clay soil barrier layer;
- minimal flow allowed through cover system;
- less tendency for lateral gas migration (than a barrier-type cover system);
- increased stability of cover system (than a geomembrane cover system);
- less susceptibility for long-term degradation (than a cover system that utilizes geosynthetic materials, whose performance may degrade in the long-term);

Economic Effects

- potential for cost savings over the prescriptive cover system;

Other Issues

- ease of construction;
- ease of maintenance and repair;
- ease of post-closure development; and

- accommodation of deeper-rooted vegetation.

The potential for barriers that may impact the successful implementation of a ET cover system can be summarized as follows:

Environmental Protection

- satisfactory performance more dependent on proper design (modeling) than a barrier-type cover system;

Economic Effects

- conditional approval delays withdrawal of financial assurance funds for final cover construction;

Other Issues

- technology may not be applicable to all sites, based on site climate, configuration of site and availability of compatible materials; and
- deviation from regulations requires demonstration that alternative cover system achieves performance goals.

4.4.2 Capillary Break Cover System

4.4.2.1 General Description

A capillary break cover system is an evapotranspirative cover system that uses a layering sequence that inhibits infiltration by fully utilizing capillary suction within the cover soils. A capillary break cover system is similar to a monolithic ET cover in that it is dependent upon the evaporation and transpiration characteristics of the cover soil to minimize infiltration. However, proper design of a capillary break cover system allows the storage capacity of the cover soil to be maximized. In addition, the capillary break cover facilitates the collection of landfill gas from the capillary break layer (which the ET cover does not include).

The most basic capillary break cover system consists of two layers, as shown in Figure 4.9. The upper storage layer typically consists of a fine silty sand with the following characteristics:

- moisture may be retained by capillary action; and
- moisture may be released to the atmosphere through evaporation and transpiration.

The capillary break layer typically consists of coarse materials such as gravel and/or coarse sand, incapable of sustaining capillary tension. The capillary break cover system functions by retaining infiltrating liquid in the fine-grained layer overlying the coarse layer. “This phenomenon, known as the capillary effect, occurs as a result of the suction - pore size relationship in unsaturated porous media. The system relies on the ability of the fine-grained material to retain and temporarily store water by using capillary forces to overcome gravitational forces. The water stored in the fine-grained material storage layer evaporates (or is transpired by vegetation) during dry periods. This evapotranspiration restores the storage layer's capacity to retain water. The capillary-break layer provides a layer that cannot draw water out of the fine-grained material as the soil suction the capillary-break layer generates are much lower than the soil suction the fine-grained materials generate.” (Jesionek and Dunn, 1997). In this manner, the capillary break maximizes the storage capacity compared to the monolithic soil layer of an ET cover, where soil suction continually draws moisture downward towards the waste.

4.4.2.2 Detailed Description and Process Options

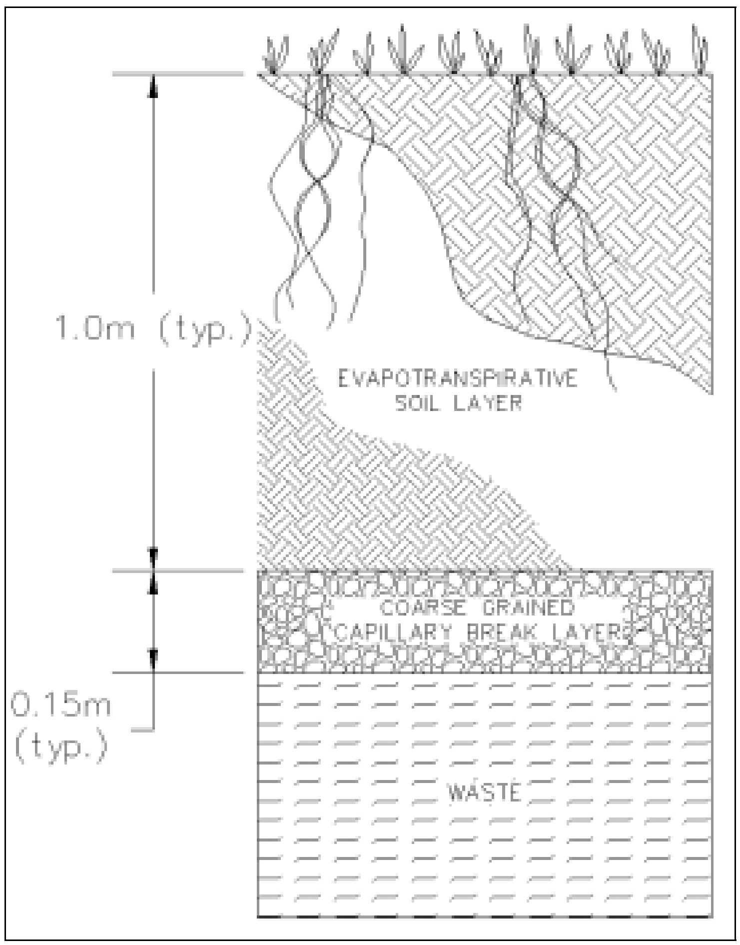
For the design of a capillary break cover system, the following primary criteria should be considered:

- the required storage capacity of the storage (fine material) layer;
- the capillary force of both the fine material layer and the capillary break (coarse material) layer; and
- the evapotranspiration characteristics of the storage layer.

Capacity of the Storage Layer

To design the capillary break cover system to function properly, the water balance characteristics at the site must be considered to provide a storage layer that has sufficient capacity to store the volume of liquid that infiltrates without allowing seepage into the underlying capillary break layer and to restore the storage capacity through evaporation and transpiration during dry periods. Water balance characteristics are defined by site precipitation and evaporation characteristics, surface vegetation coverage, and vegetative layer transpiration characteristics.

Figure 4.9: Capillary Break Cover System **Source: Kavazanjian, 2001**



Capillary Forces

The soil materials selected for the storage layer and capillary break layer must be compatible in that the capillary forces generated in the storage layer must be much greater than the soil suction generated in the underlying capillary break layer. This allows the infiltrating liquid to be stored in the storage layer without seeping into the underlying capillary break layer. Unless a filter geotextile is used, the underlying coarse layer must also meet filter criteria to mitigate infiltration of the overlying finer grained soil into the capillary break layer.

Evapotranspiration of the Storage Layer

The soil selected for the storage layer should have characteristics that balance evapotranspiration with storage capacity. To regain storage capacity after significant infiltration has occurred over a short period of time (i.e., during and after a heavy rain event), liquid in the storage layer should evaporate or transpire quickly enough that the moisture content of the storage layer does not increase steadily over time. This allows a moisture condition below the field capacity of the storage layer to be maintained in the fine-grained storage layer.

4.4.2.3 Global Application of Technology and Case Histories

The capillary break cover system is particularly applicable to arid and semi-arid climates, such as is found in parts of California. This technology has been employed at several locations nationwide, including the Gaffey Street Sanitary Landfill in Los Angeles, California. The following excerpt from Evans et. al [2000], provides a description of the capillary barrier implemented at the site as well as the design procedures and regulatory approval process.

"The Gaffey Street Sanitary Landfill is an inactive California Class III (municipal solid waste) landfill which is owned by the City of Los Angeles (the City) Bureau of Sanitation (BOS)." The landfill received waste between 1957 and 1977.

"At the time the Gaffey Street Sanitary Landfill ceased waste acceptance, the State of California did not have formal requirements for landfill final covers. The site was covered with a varying thickness of available soil upon cessation of operations."… "The City is now developing the Gaffey Street Sanitary Landfill as a recreation park (primarily as soccer fields)."… "Because of the semi-arid location of the site, the proposed end use of the closed Landfill, and the Landfill status (inactive for some years), a capillary barrier cover was proposed for the final cover. The capillary barrier cover will consist of, from top to bottom:

- one foot (0.3 m) of vegetative soil;
- three feet (0.9 m) of silty sandy soil;
- an 8 oz/yd^2 (271 g/m) filter geotextile;
- six inches (0.15 m) of drainage gravel; and
- an 8 oz/yd^2 (271 g/m) filter geotextile.

"After construction of the capillary barrier final cover, a 'smart' irrigation system and a soil moisture monitoring system will be installed at the site." This 'smart' irrigation system will minimize the possibility of overwatering the capillary barrier final cover while sustaining landscaping. "The 'smart' irrigation control system for the landfill will consist of a flow meter, control valves, a self-tipping rain bucket, and an evapotranspiration (ET) gauge."

"A soil moisture monitoring system, required for final approval of the cover, will be used to measure the effectiveness of the 'smart' irrigation system, although the two system are not hardwired together. The soil moisture monitoring system will be comprised of sensors (either time domain reflectometry or neutron probes) installed in two locations and at varying depths within the cover. If measurements from the soil moisture monitoring system indicate that excess moisture is migrating towards the base of the cover, the irrigation algorithms will be adjusted."

"Among the state regulatory requirements for an alternative final cover is that it provide equivalent (or superior) protection to groundwater compared to the prescriptive final cover." To demonstrate that the proposed capillary barrier final cover provides equivalent or superior groundwater protection compared to the prescriptive clay cover, a site-specific unsaturated flow analysis was performed**.** Conditional regulatory approval of the cover may be granted, depending on the results of the unsaturated flow analysis. "Final regulatory approval of the cover is typically contingent upon two years of soil moisture monitoring in the final cover coupled with confirmatory computer modeling. If no sustained rainfall occurs during the two-year performance monitoring period, moisture will be artificially applied [by the "smart" irrigation system] in a manner that emulates a 100-year storm for evaluation of the alternative cover."

The capillary break cover system has been approved and constructed at the Gaffey Street Sanitary Landfill.

4.4.2.4 Research Studies

Studies are being performed nationwide to evaluate the performance of a variety of alternative cover systems, including capillary break cover systems. The following two studies are particularly applicable to California because they are evaluating the performance of landfill cover systems in arid and semi-arid environments.

- The Alternative Landfill Cover Demonstration (ALCD), sponsored by the Department of Energy, is a 5-year (minimum) study of the performance of six test cells (4 alternative cover systems and 2 prescriptive cover systems) constructed at a site near Albuquerque, New Mexico (USDOE, 2000).
- The Alternative Cover Assessment Program, sponsored by the USEPA, is establishing field demonstrations at 12 sites nationwide to evaluate the performance of various alternative cover systems over a five-year period. Currently test sections of evapotranspiration cover systems are being installed and monitored nationwide, though it is expected that the study will be expanded to include other designs for alternative cover systems.

However, both of these studies are "in progress", so no definitive findings are available from them at this time.

4.4.2.5 Technologies in Combination

No potential for added benefit (or risk) from applying a capillary break cover system in combination with the other technologies discussed in this report have been identified.

4.4.2.6 Application in California

In general, non-barrier cover systems, including capillary break cover systems, have been developed with arid and semi-arid climates in mind, as are found in most parts of California. Studies are ongoing to evaluate the performance of these types of alternative cover systems in arid and semi-arid climates. These studies generally employ conditional approvals, wherein the owner is prohibited from withdrawing money from financial assurance funds until after several years of post-construction monitoring has been completed. While regulations that allow for engineered alternatives to the prescriptive cover system facilitate the application of alternative cover systems in California, long-term conditional approvals may dissuade some owners from employing alternative covers even in cases where it is recognized that the prescriptive cover (i.e., a clay barrier cover) will not perform satisfactorily.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study does not identify any landfill sites in California have planned or installed capillary break final cover systems.

4.4.2.7 Evaluation of Benefits and Barriers

The potential benefits of implementing a capillary break cover system instead of a typical final cover system include the following:

Environmental Protection

- minimal flow allowed through cover system;
- superior resistance to cracking in arid / semi-arid climates over clay soil barrier layer;
- allows landfill to “breathe” (mitigates lateral gas migration);
- increased stability of cover system (over geomembrane cover system);
- provides a blanket high permeability layer that can be used for landfill gas control; and

Economic Effects

- potential for cost savings over the prescriptive cover system.

The potential for barriers that may impact the successful implementation of a capillary break cover system can be summarized as follows:

Environmental Protection

- adequate performance is more dependent on proper design (modeling) than a barrier-type cover system;
- “breakthrough” of the capillary layer can lead to excessive infiltration to the waste;

Other Issues

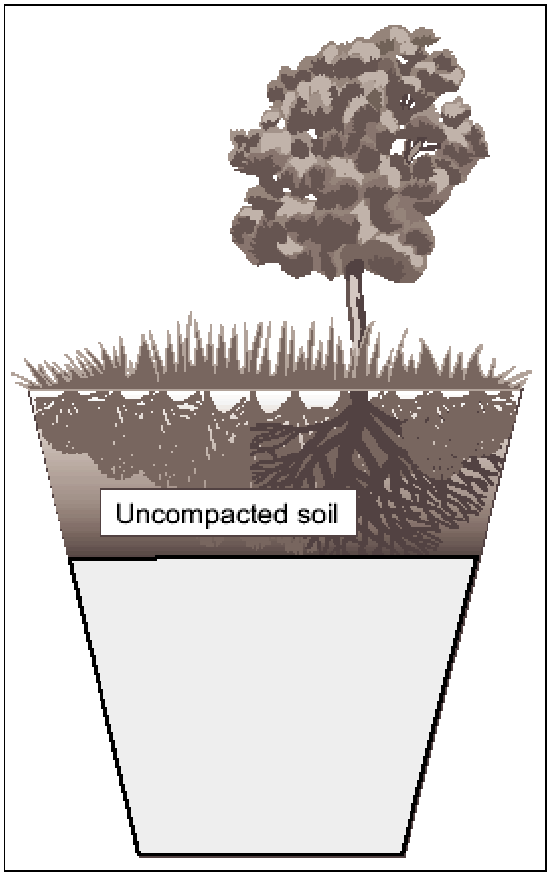
- technology may not be applicable to all sites, based on site climate, configuration of site and availability of compatible materials; and
- deviation from regulations requires demonstration that alternative cover system achieves performance goals.

4.4.3 Phytoremediation Cover System

4.4.3.1 General Description

Similar to an ET cover system, a phytoremediation cover system uses a monolithic soil cover and relies on the storage capacity, evaporation and transpiration characteristics of the cover soil to minimize percolation into the waste mass. However, unlike an ET cover system, a phytoremediation cover system is designed to incorporate a variety of vegetative types, from grasses to trees, which minimize infiltration and enhance degradation of the waste mass. A phytoremediation cover may actually rely upon intrusion of the root system into the waste or contaminated soil to facilitate degradation. A typical phytoremediation cover system is shown in Figure 4.10.

Figre 4.10: Phytoremediation Cover System **Source: USEPA, 2000**



4.4.3.2 Detailed Description and Process Options

A phytoremediation cover system uses the following mechanisms to restrict infiltration and accelerate degradation:

- hydraulic control: removal of water through uptake and consumption by vegetation;
- phytodegradation: breakdown of contaminants consumed by vegetation through plant processes;
- rhizodegradation: biodegradation of contaminants in the root zone;
- phytovolatilization: consumption and transpiration of contaminants by vegetation resulting in the release of the contaminant (in original or modified form) to the atmosphere; and possibly
- phytoextraction: consumption and translocation of contaminants by vegetation resulting in the removal of contaminant by harvesting vegetation (i.e., collecting leaves, cutting grass) (USEPA, 2000).

To optimize the performance of these mechanisms, the following criteria should be considered during the design phase:

- contaminant types and concentrations;
- optimal root depth;
- applicable plant types;
- soil properties;
- gas production; and
- climatic conditions (USEPA, 2000).

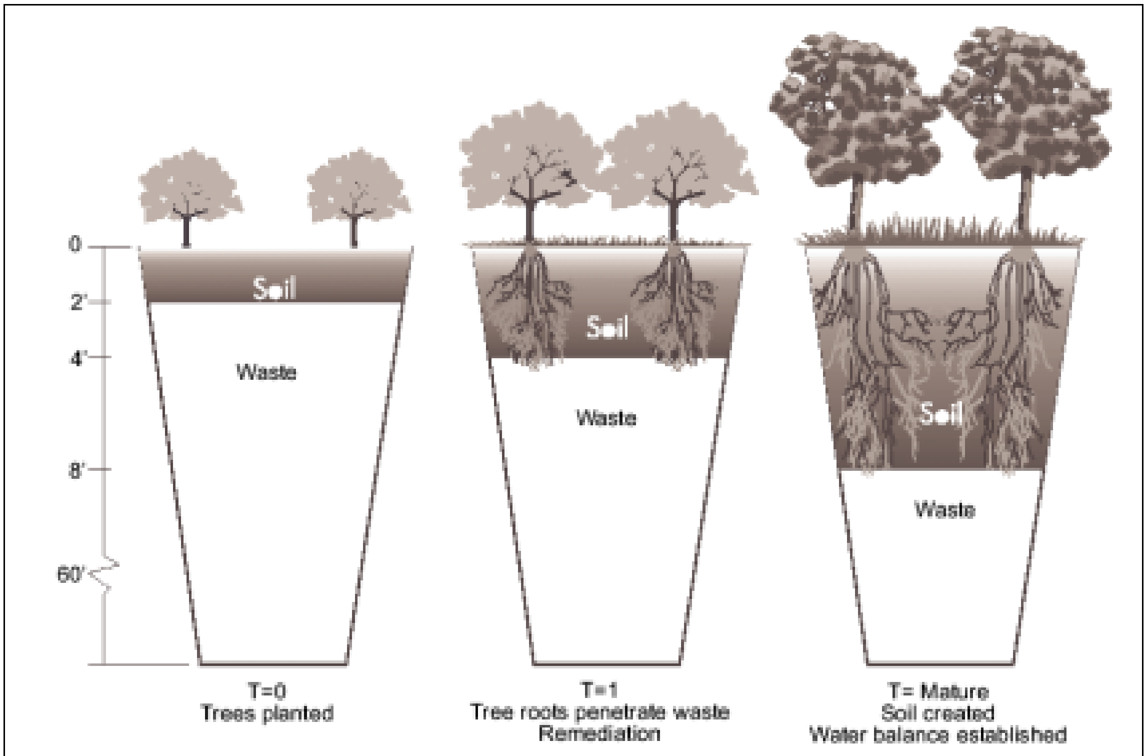
Contaminant Types and Concentrations

It should be recognized that the application of a phytoremediation cover system may not be feasible at municipal solid waste landfills if the contaminants within the waste mass are at phytotoxic levels.

Optimal Root Depth

Degradation will be enhanced to the maximum depth of the root mass, so it is recommended that the selected vegetation have a root zone at least as deep as the top of the waste mass. An optimized phytoremediation cover design balances the rate of root zone development with the rate of waste degradation. The development of the root zone with time, as well as the changing function of the cover system (from remediation to hydraulic control), is depicted in Figure 4.11.

Figure 4.11: Development of Phytoremediation Cover System Source: USEPA, 2000



Notes: T = time

Applicable Plant Types

Phytoremediation cover systems have been designed using poplar trees and various varieties of grasses. “Ideally, the vegetation selected for the system should be a mixture of native plants and consist of warm- and cool-season species” (USEPA, 2000).

Soil Properties

The cover soils for a phytoremediation cover should consist of silts or mixed soils with sufficient fines content to provide a high storage capacity, but also able to support vegetation.

Gas Production

It should be recognized that the application of a phytoremediation cover system may not be feasible at municipal solid waste landfills if a large amount of landfill gas is expected to be generated. Prolonged exposure to landfill gas can be toxic to vegetation.

Climatic Conditions

Phytoremediation cover systems have been found to be most applicable to arid and semi-arid climates, though the system may be designed to accommodate high humidity and high precipitation rates that occur in other climates. To allow adequate evapotranspiration to occur in humid climates, the cover soil may need to be thicker than would be applied in arid/semi-arid climates. In areas of high rainfall, the system may need to be designed to accommodate more transpiration or allow a higher storage capacity in the cover soil.

4.4.3.3 Global Application of Technology and Case Histories

Phytoremediation has been implemented at landfill sites worldwide. “Introduction to Phytoremediation” (USEPA, 2000) provides a list of sites where phytoremediation has been implemented. Table 4-E contains excerpts from that list, providing information on the sites identified as landfills. It should be recognized that the USEPA list does not distinguish between landfill sites where phytoremediation was implemented in the form of a cover system and sites where phytoremediation was implemented for soil and groundwater remediation.

The following excerpts from USEPA [2000], provides a description of the phytoremediation cover system implemented at the Lakeside Reclamation Landfill as well as the design procedures and regulatory approval process.

"The Lakeside Reclamation Landfill (LRL), located near Beaverton, OR, is actively receiving non-recyclable construction demolition debris for disposal on the 60-acre site." "In April 1990, a 0.6-acre prototype cap consisting of hybrid poplar trees, primarily cottonwoods, was installed on a recently filled waste cell." "The objective of the initial project was to demonstrate the application of hybrid poplar trees to effectively prevent infiltration of water to underlying waste. The prototype plot was designed to provide the data required to meet regulatory compliance and to provide enough information to close the entire landfill using this capping technique. The migration of contaminated leachate is a concern to the [regulatory agencies]... because the Tualatin River is located adjacent to the LRL." "The final cover must meet or exceed the mandatory minimum groundwater quality protection requirements."

“The cover design for the prototype cap is composed of hybrid poplars (primarily cottonwood trees) and silt loam soils. The waste cells of the landfill were initially covered with two layers of silty loam soil at a thickness of roughly 5 ft and graded at a 3% slope. The layer installed over the waste is approximately 1 ft of compacted silt loam soil that has a high-clay content. The surface layer consists of loosely placed loam soil at a depth of 4 ft."

"Hybrid poplars were selected primarily because of the research being conducted at the University of Iowa using these trees for buffer systems. Secondly, the landfill borders the Tualatin River riparian area populated by both deciduous and conifer trees, thus providing evidence that the site is capable of growing hybrid poplars. Thirdly, the hybrid poplars had a relatively long growing season, extending from mid-March through November. Finally, hybrid poplars offered the potential for dense tree population, deep root placement, and large quantities of water to be transpired per tree. In April 1990, approximately 7,455 tree cuttings were planted on the 0.6-acre site (60 ft x 600 ft), for an average plant density of 3.4 ft^2 per tree. Three different hybrid poplar varieties were planted in the prototype cover."

"Based on the results of the initial prototype cap, the demonstration was expanded to a 2-acre area in 1991." "To diversify the cultivars base, 18 new tree varieties were planted. The new tree cuttings planted were composed of varieties that had the capability to grow in the Pacific Northwest region. For the 1992 growing season, a cool-season grass crop, rye grass, had been established on a portion of the demonstration site. The addition of grasses to the design improved the cover by increasing the evapotranspiration process during the tree's dormant period, controlling weed growth, and increasing the overall soil stability during the early periods of tree development. In addition, as an alternative to grass, another portion of the cover was mulched with bark chips." "The survival rate for the hybrid poplar trees planted in April 1990 was greater than 85% and there were no observed losses for the 1991 growing season."

Table 4-E: Landfill Sites Using Phytoremediation Cover Systems **Source: USEPA, 2000**

Project Name / Location	Size of Area	Primary Contaminant	Media and Properties	Vegetative Type	Date Planted
ACME Landfill, NC	NP	NP	groundwater	poplar	NP
Barje Landfill, Slovenia	10 acres	heavy metals, other	subsurface soil	hybrid poplar	1993, 1994
Bluestem Landfill #1, IA	3 acres	leachate	subsurface soil	hybrid poplar and grasses	1994
Bluestem Landfill #2, IA	5 acres (2 test plots)	NP	subsurface soil	hybrid poplar and grasses	1994
City of Glendale Landfill, AZ	1 acre (2 test covers)	NP	silty sand soils	ryegrass, bermuda grass	NP
Coffin Butte Landfill, OR	14.4 acres overland polishing system	landfill leachate	leachate	grass, hay and native trees	existing
Former Municipal Landfill, NY	3 acres border area	heavy metals	groundwater	hybrid poplars	June-July 1998
Fort Carson (Landfills 5 and 6), CO	20 – 40 acres	municipal and mixed waste	NP	NP	NP
Green II Landfill, OH	30 acres	VOCs and other organics in leachate	leachate and soil	hybrid poplar and hybrid willows	Fall 1998
Grundy County Landfill, IA	5 acres, 2 acres	leachate	subsurface soil	hybrid poplar	1993,1994
Hillsboro Landfill Wetlands, OR	54 acres	no waste	groundwater	vegetative cover	NP
Hollola Landfill, Finland	3 hectares	ash, oily waste	NP	NP	NP
Industrial Landfill, TN	3 acres	VOCs and thallium	groundwater	hybrid poplars with grass	Spring 1998
Johnson County Landfill, IA	9 acres	halogenated volatiles, heavy metals, other	subsurface soil	hybrid poplars and grass	1992,1993
Lakeside Reclamation Landfill, OR	0.6 acres, 8 acres	landfill leachate	soil and water	hybrid poplar and grass	April 1990
Lanti Landfill, Finland	17 hectares	ash	NP	NP	NP
New Hampshire Landfill, NH	NP	halogenated volatiles	NP	NP	NP
Tama County Landfill, IA	12 acres, 14 acres	leachate	shallow soil	hybrid poplar	1993-1995
USA Waste Riverbend Landfill, OR	14.3 acres irrigated	VOCs, heavy metals, other	leachate	hybrid poplar, grass	1992
Woodlawn Landfill, MA	~21 acres	halogenated volatiles and metals	groundwater	hybrid poplars	pending approval

NP = Information not provided

"Lysimeters, piezometers, and tensiometers were installed in May 1990 to collect water samples and measure moisture content in the soil cover. Four instrument 'nests' were placed on the landfill cover. Each instrument nest contained three suction lysimeters and three ceramic cup tensiometers installed at 1-, 3-, and 5-ft depths. Another instrument nest was installed off the prototype cap to provide background measurements." "Weekly tensiometer data were collected to determine the moisture content of soils at various locations both on and off the 0.6 acre cover." "From September to December 1990, the tensiometer indicated moisture content, at the 1-ft horizon, fluctuated considerably from saturated to very dry depending on precipitation, solar intensity, air temperature, relative humidity, ground cover, and shade at the soil surface. In addition, during the growing season, there was no apparent impact on the tensiometer reading at the 3- and 5-ft depths, implying no change in the moisture content. Significantly less water was present at the 5-ft soil profile in 1991 than in 1990. In addition, moisture content observed in December 1991 indicated the soil profile had more storage capacity available than was available in measurements taken the previous year."

"To date, the cap has expanded to a total of 8 acres and has demonstrated no deep percolation. For the final closure of the landfill, the vegetative cover will enclose an area of approximately 40 acres."

4.4.3.4 Research Studies

Studies are being performed nationwide to evaluate the performance of a variety of alternative cover systems, including phytoremediation cover systems. The following two studies are particularly applicable to California because they are evaluating the performance of landfill cover systems in arid and semi-arid environments.

- The Alternative Landfill Cover Demonstration (ALCD), sponsored by the Department of Energy, is a 5-year (minimum) study of the performance of six test cells (4 alternative cover systems and 2 prescriptive cover systems) constructed at a site near Albuquerque, New Mexico (USDOE, 2000).

- The Alternative Cover Assessment Program, sponsored by the USEPA, is establishing field demonstrations at 12 sites nationwide to evaluate the performance of various alternative cover systems over a five-year period. Currently test sections of evapotranspiration cover systems are being installed and monitored nationwide, though it is expected that the study will be expanded to include other designs for alternative cover systems.

However, both of these studies are "in progress", so no definitive findings are available from them at this time.

4.4.3.5 Technologies in Combination

Use of **an exposed geomembrane cover system** or a **phytoremediation cover system** may not be applicable in conjunction with some technologies for enhanced degradation of the waste such as **leachate recirculation, air injection** or **passive aeration**. The build-up of landfill gas under these types of cover systems is detrimental to their effectiveness.

4.4.3.6 Application in California

In general, non-barrier cover systems, including phytoremediation cover systems, have been developed with arid and semi-arid climates in mind, as are found in most parts of California. Studies are ongoing to evaluate the performance of these types of alternative cover systems in arid and semi-arid climates. These studies generally employ conditional approvals, wherein the owner is prohibited from withdrawing money from financial assurance funds until after several years of post-construction monitoring has been completed. While regulations that allow for engineered alternatives to the prescriptive cover system facilitate the application of alternative cover systems in California, long-term conditional approvals may dissuade some owners from employing alternative covers even in cases where it is recognized that the prescriptive cover (i.e., a clay barrier cover) will not perform satisfactorily.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study does not identify any landfill sites in California that have planned or implemented phytoremediation final cover systems.

4.4.3.7 Evaluation of Benefits and Barriers

The potential benefits of implementing a phytoremediation cover system instead of a typical final cover system include the following:

Environmental Protection

- equivalent or superior isolation of waste and erosion resistance than the prescriptive cover system;
- accelerated stabilization of waste mass;
- superior resistance to cracking in arid / semi-arid climates over clay soil barrier layer;
- minimal flow allowed through cover system;
- increased stability of cover system (than a geomembrane cover system);
- less susceptibility for long-term degradation (than a cover system that utilizes geosynthetic materials, whose performance may degrade in the long-term), increasing environmental performance;

Economic Effects

- less susceptibility for long-term degradation (than a cover system that utilizes geosynthetic materials, whose performance may degrade in the long-term), potentially reducing post-closure costs; and

Other Issues

- ease of construction over a typical cover system.

The potential for barriers that may impact the successful implementation of a phytoremediation cover system can be summarized as follows:

Environmental Performance

- satisfactory performance more dependent on proper design (modeling) than a barrier-type cover system;
- effectiveness and long-term performance dependent on survivability of cover vegetation;

Other Issues

- technology may not be applicable to all sites, based on site climate, configuration of site and availability of compatible materials; and

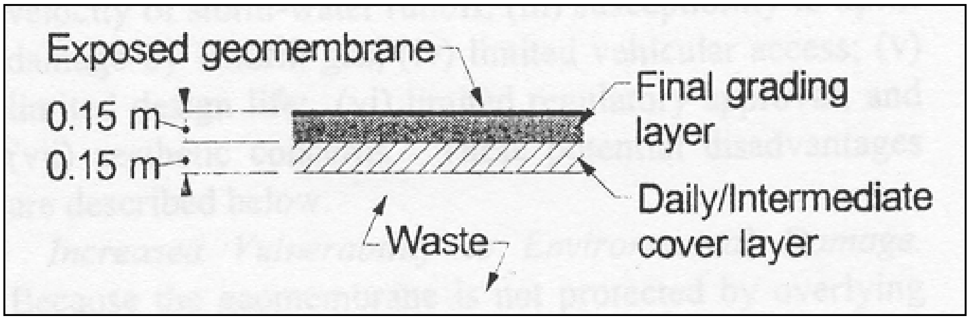
- deviation from regulations requires demonstration that alternative cover system achieves performance goals.

4.4.4 Exposed Geomembrane Cover System

4.4.4.1 General Description

An exposed geomembrane cover system (EGCS) generally consists of a geomembrane overlying a foundation soil layer, as shown in Figure 4.12, without drainage, topsoil or vegetation layers that may be included in a typical cover system.

Figure 4.12: Exposed Geomembrane Cover System **Source: Gleason et al., 1998**



An EGCS may be considered as a viable alternative to a typical cover system in certain special situations where aesthetics are not a significant issue, infiltration control is critical, or stability concerns preclude placement of a vegetative cover soil layer. An EGCS is most applicable to sites with the following conditions:

- the design life of the cover system is on the order of 10 to 20 years or less;
- future removal of the cover system is anticipated for landfill mining or placement of additional waste;
- additional soil or waste is to be placed on top of the cover at a later date;
- the landfill sideslopes are steep, precluding the placement of soil over geomembrane; or
- availability or cost of cover soils prohibits the application of a typical cover system (Gleason, Houlihan and Palutis, 2001).

4.4.4.2 Detailed Description and Process Options

The design process for an EGCS requires that several criteria be considered that are not generally considered in the design of a typical final cover system. These criteria include the following:

- resistance to sunlight;
- resistance to low temperatures;
- resistance to downslope creep;
- resistance to puncture from hail stones;
- resistance to wind damage; and
- potential for damage due to maintenance, vandalism or animals (Gleason, Houlihan, and Giroud, 1998).

Design methodology has been developed to allow consideration of each of these criteria, and have been published by Gleason, Houlihan, and Giroud (1998).

Due to the prolonged exposure to sunlight, a geomembrane that has sufficient UV resistance should be selected for use in an EGCS. Some geomembrane materials used in landfill construction, such as polyvinyl chloride (PVC), may not be appropriate for use with an EGCS due to low UV resistance. Depending on the configuration of the site, PVC may also be deemed unsuitable due to low tensile strength and the associated potential for downslope creep as well as low puncture resistance.

High density polyethylene (HDPE), particularly if it is stabilized with carbon black, is extremely resistant to UV degradation. However due to its relatively low ductility and toughness, if a site has steep slopes, experiences hail storms, or has a potential to incur other damage due to maintenance, vandalism or animals, then HDPE may not be a suitable material for use with an EGCS.

An alternative to HDPE is scrim-reinforced polypropylene (PP-R). The scrim reinforcement resists damage due to wind uplift, downslope creep and puncture. Depending on the site conditions and lifetime of the EGCS, PP-R can also provide sufficient UV resistance to allow prolonged exposure to sunlight.

The EGCS must be designed to resist wind uplift. The designer should specify a geomembrane with sufficient tensile strength and design an anchor system to withstand wind uplift. Anchoring of the geomembrane is accomplished by the installation of anchor trenches at appropriate intervals and, if necessary, use of surface anchoring systems, such as sandbags or tires linked together with rope. The long-term exposure resistance and maintenance requirements of the surface anchor system should be taken into consideration during design.

Two side affects of installing a geomembrane without overlying soils that must be considered when designing the system, are (1) an increase in surface water volume / flow rate and (2) an increased potential for uplift of the liner system due to landfill gas accumulation. With a typical cover system the cover soils slow down the runoff of surface water and allow some infiltration to occur. With an EGCS, surface water runs off quickly with minimal evaporation. Therefore, the surface water control system should be designed to accommodate this increase in volume and time of concentration.

The lack of overburden on the geomembrane results in an increased risk for uplift due to the accumulation of landfill gas under the geomembrane. If a landfill gas system must be installed to effectively handle landfill gas, it may also be employed to reduce the risk for wind uplift (Gleason, Houlihan and Palutis, 2001). The landfill gas system may also be used to mitigate the effects of wind uplift by applying a negative pressure (suction) on the bottom side of the cover. Geomembrane selection and anchor trench design must consider the total tensile load expected from wind and gas uplift.

4.4.4.3 Global Application of Technology and Case Histories

Four sites in the United States have been identified where EGCS technology has been implemented, including:

- a site in Delaware, where an ECGS was used to minimize leachate production and to provide a long-term cover system over waste that would later be reclaimed;
- a site in Maine, where the landfill had reached interim final grades that could not be exceeded due to stability issues (consolidation of underlying material will allow placement of additional waste in the future);

- a site in Florida, where an ECGS was constructed in one area to provide odor control prior to construction of a final cover system and in another area to provide a temporary cover prior to placement of additional waste; and
- a site in Louisiana, where severe erosion of steep landfill sideslopes precluded the use of a conventional landfill cover system (Gleason, Houlihan and Palutis, 2001).

The following excerpts from Gleason, Houlihan and Palutis, 2001, and Germain, 1997, provide a case history for the site in Delaware where an ECGS was installed. Cells 1 and 2 of the landfill consist of "two double-lined cells that have been filled to form one monolithic landfill with an area of approximately 17-ha. Solid waste was placed in Cell 1 from 1984 to 1988; solid waste was placed in Cell 2 from 1988 to 1997. In 1997 and 1998, a long-term EGCS was constructed over the Cell 1 and 2 Landfill" (Gleason, Houlihan and Palutis, 2001).

At this site, "an exposed geomembrane was selected for several reasons. First it satisfied the criteria to limit leachate production. Second, less maintenance was expected for this cap than for a conventional Subtitle D cap. The third reason concerned the ultimate end use; the DWSA [Delaware Solid Waste Authority] considers landfill mining as the best option for closing a landfill, including incineration of the recovered combustible waste and reuse of the landfill footprint. This cap system provides for possible mining in the future. Finally, capital costs were expected to be less because the top soil layers were not installed" (Germain, 1997).

"The geomembrane component of the EGCS is a 0.9-mm thick green polypropylene geomembrane with a polyester scrim reinforcement. Based on the local building code for structures in the area, the design wind velocity was selected to be 130 km/hr. The landfill has 4H:1V slopes, is approximately 40-m high, and has cover benches with corresponding drainage swales and geomembrane anchors spaced at 12-m vertical intervals (for an exposed geomembrane length of approximately 50 m). The constructed geomembrane anchor trench is located at each cover bench and has a cross sectional area of 2.3 m^2."

"The limited availability [of] cover soil material in the region and the possibility of future waste mining and/or capacity recovery at the site made the EGCS an economically attractive option for this landfill. By constructing and EGCS for the Cell 1 and 2 Landfill, a cost savings of approximately $60,000 per hectare was realized, compare to constructing a typical final cover system" (Gleason, Houlihan and Palutis, 2001).

4.4.4.4 Research Studies

Very little existing or on-going research on the applicability and effects exposed geomembrane cover systems has been identified during this study. Primary sources for the development of this discussion consisted of a review of experiences at a few sites, described in more detail in Section 4.4.4.3. To fully evaluate the suitability of an exposed geomembrane cover system for application at a particular site, further evaluation of experiences at existing sites is recommended.

4.4.4.5 Technologies in Combination

Use of **exposed geomembrane cover systems** as sites where **landfill mining** is planned can reduce costs and simplify operations.

Use of **an exposed geomembrane cover system** or a **phytoremediation cover system** may not be applicable in conjunction with some technologies for enhanced degradation of the waste such as **leachate recirculation, air injection** or **passive aeration**. The build-up of landfill gas under these types of cover systems is detrimental to their effectiveness.

4.4.4.6 Application in California

In general, exposed geomembrane cover systems are applicable to sites in California, for limited term applications (up to 10 to 20 years). However, sites with high winds or aesthetic requirements may not be suitable for application of this technology. There are no barriers in the current regulations to the application of this technology.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study identifies one landfill in California where an exposed geomembrane cover system is proposed:

- Azusa Land Reclamation Company Landfill.

4.4.4.7 Evaluation of Benefits and Barriers

The potential benefits of implementing an EGCS instead of a typical final cover system include the following (Gleason, Houlihan and Palutis, 2001):

Environmental Protection

- reduced post-installation settlement of waste due to reduced load from cover system, reducing the potential for surface water infiltration;
- reduced hydraulic head on geomembrane cover barrier, reducing the potential for surface water infiltration;

Economic Effects

- reduced construction cost;
- reduced annual operation and maintenance requirements;
- increased landfill volume by eliminating cover soils;

Other Issues

- easier access to materials for landfill mining;
- slope stability of veneer cover soil is not a design concern; and
- ease of inspection.

The potential for barriers that may impact the successful implementation of a EGCS can be summarized as follows (Gleason, Houlihan and Palutis, 2001):

Environmental Protection

- lack of cover soil results in an increased vulnerability to environmental damage;
- increased susceptibility to uplift by landfill gas;

Economic Effects

- limited design life, requiring replacement of the cover typically once every 10 to 20 years;

Other Issues

- more difficult to remediate ponding due to differential settlement on decks and benches;

- increased volume and velocity of surface water runoff;
- vehicle access to cover system is limited (i.e., for surface water system maintenance);
- deviation from regulations may require demonstration that EGCS achieves performance goals;
- aesthetics concerns; and
- limited options for post-closure use.

4.4.5 Delayed Closure

4.4.5.1 General Description

As suggested by the USEPA (1991), it may be appropriate to propose the installation of an intermediate cover instead of a final cover for two to five years following the end of waste placement to allow anticipated settlement of the waste mass occur. This concept is not new, but it has not yet been widely implemented. Sites continue to be closed soon after waste placement. This practice reduces the generation of leachate and may allow the site to be redeveloped quickly, but dramatically slows the degradation process. By allowing a delay in closure, the waste continues to degrade, reducing the potential for long-term impacts on the environment.

The practicality of allowing delayed closure is governed by several things, including:

- <u>waste characteristics</u>: more marked increases in degradation are expected to occur in wastes with a high organic content;
- <u>site location</u>: for sites in urban areas there may be pressure to close quickly, precluding the application of delayed closure; and
- <u>containment system characteristics</u>: delayed closure is in general not recommended for sites without an LCRS or base liner system.

4.4.5.2 Global Application of Technology and Case Histories

No sites have been identified where delayed closure has been approved by a regulatory agency to allow enhanced degradation of the waste mass prior to closure. One site, Millikin Landfill in California, is reportedly nearing the end of a four to five year delayed closure, though the purpose of this delay has not been identified and regulatory approval of the delay has not been verified.

4.4.5.3 Research Studies

Very little existing or ongoing research on the applicability and effects of delayed closure has been identified during this study. To fully evaluate the suitability of one of the alternative base containment systems considered in this study for application at a particular site, further evaluation of experiences at existing sites is recommended.

4.4.5.4 Technologies in Combination

Delayed closure of a landfill may be particularly applicable if the landfill incorporates a technology for enhanced degradation prior to closure, such as an **anaerobic bioreactor landfill** or an **aerobic/semi-aerobic landfill**. By delaying closure, the waste mass is allowed to continue to degrade and stabilize, without excessive settlement of the final cover or accumulation of landfill gas below the cover system.

4.4.5.5 Application in California

Delayed closure is generally applicable to sites throughout California, depending on the characteristics of the waste, the local climate, and the type of base containment system. Delayed closure may not be applicable in areas where urban development has encroached upon a site, as such sites are generally pressured to close shortly after waste acceptance is ceased in order to mitigate nuisance concerns such as odors and vectors.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study does not identify any landfill sites in California that have planned or implemented a delayed closure strategy.

4.4.5.6 Evaluation of Benefits and Barriers

The potential benefits of allowing delayed closure, as opposed to installing a typical final cover system include the following:

Environmental Protection

- reduced potential for post-closure environmental impacts due to accelerated stabilization of the waste;
- reduced post-closure settlement, reducing the potential for infiltration in the long-term;
- improved performance of the final cover system due to the accelerated stabilization of waste; and
- decrease in long-term environmental risk due to accelerated stabilization of the waste mass.

Economic Effects

- reduced post-closure maintenance and potential for shortened length of the monitoring period with subsequent savings in post-closure costs;

The potential for barriers that may impact the successful implementation of delayed closure can be summarized as follows:

Environmental Protection

- increased potential for pre-closure environmental impacts due to absence of final cover and accelerated waste degradation;

Other Issues

- technology may not be applicable to all sites, based on waste characteristics, site locations and containment system components; and
- deviation from regulations requires regulatory approval.

5 Remediation Technologies

Landfill remediation technologies evaluated herein include technologies for landfill gas destruction and reuse, waste remediation, and leachate remediation. Technologies for waste remediation include aerobic remediation through passive aeration and air injection and landfill mining. The leachate remediation technology addressed herein is leachate recirculation.

5.1 Landfill Gas Applications

The technologies associated with extracting and destructing landfill gas (LFG) are generally mature. The LFG extraction and destruction systems typically consist of:

- a wellfield to collect LFG from the waste, comprised of vertical wells that are drilled into the waste mass or horizontal collectors that are constructed within the waste mass as waste is placed;
- header pipelines that convey LFG from the wellfield to a flare;
- lateral pipes that connect the wells or horizontal collectors to header pipelines;
- a blower(s) used to apply a vacuum to the wellfield;
- a flare to destruct the LFG;
- a condensate collection system; and
- controls to operate and manage the entire system.

There are two common vertical well design types: a) large diameter wells (typically around 36 inches) that are placed one or two per acre; and b) small diameter wells (typically less than 24 inches) that are placed at a rate of four or more per acre. Horizontal collectors are used in some landfills in place of or in conjunction with vertical wells. These collectors are typically constructed within successive lifts of the waste mass as it is being placed, spaced approximately 100 to 200 feet horizontally in vertical lifts separated 30 to 60 feet. The collectors are typically offset horizontally in each successive lift.

Most new and emerging technologies are in the area of collecting and converting LFG to other forms of energy, though there are also some new innovations in the area of LFG destruction. The remainder of this section identifies emerging technologies in the LFG industry.

5.1.1 LFG Destruction

5.1.1.1 General Description

The basic technology for the destruction of LFG, with variations, is well established and has not changed much during the past ten years. However, two recent innovations are high-temperature flare technology and flameless noncatalytic oxidation.

Using a booster to pressurize the LFG and increase its temperature, it is possible to completely oxidize methane found in LFG using the high-temperature flare. Also, flares may now include sensors for continuously analyzing concentrations of contaminants in the combustion chamber.

Flameless noncatalytic oxidation technology can be used to destruct LFG with methane concentrations as low as 0.3% by volume. This technology passes the LFG over a hot ceramic bed (approximately 1,000 degrees Celcius), which causes the organic compounds to oxidize and generates heat to maintain the bed temperature. This technology achieves destruction efficiencies equivalent to high-temperature flares (Haase, 2003).

5.1.1.2 Global Application of Technology and Case Histories

High-temperature flare technology has been employed at the Chapois Landfill in Belgium. The high-temperature flare stack, operating in the range of 1,200 degrees Celsius with a residence time of 0.3 seconds, has been in operation since 1999 (Haase, 2000). High-temperature flare manufacturers are reporting no detection of uncombusted hydrocarbons (i.e., destruction efficiencies close to 100%). By comparison, a standard flare operates at approximately 800 - 900 degrees Celsius, and achieves destruction efficiencies of greater than 99% of total organic compounds and greater than 98% of total non-methane organic compounds (NMOC).

Flameless noncatalytic oxidation technology has been developed and field tested for LFG applications by Haase Energietechnik GmbH. Their VocsiBox® unit was demonstrated at the closed Bemerode 1 Landfill in Hanover, Germany (Haase, 1999). This was not a permanent commercial application.

5.1.1.3 Research Studies

The Haase high-temperature flare has not been deployed in the U.S. A comparison of existing performance and emission data to U.S regulatory standards should be conducted. A demonstration project may need to be conducted prior to full-scale implementation of this technology.

The Hasse-VocsiBox® has not been demonstrated in the U.S., and it appears that a long-term commercial application for LFG has not occurred previously. A demonstration project may need to be conducted prior to full-scale implementation of this technology.

5.1.1.4 Technologies in Combination

The use of **high temperature flares** and **flameless noncatalytic oxidation** may serve to reduce the potential environmental impact of accelerated LFG production expected with **anaerobic bioreactor landfills** and **leachate recirculation**.

5.1.1.5 Application in California

Because high-temperature flares and flameless noncatalytic oxidation have not been implemented in the U.S., it is unknown whether performance and emissions standards will meet U.S. and California criteria. Compliance should be demonstrated prior to full-scale implementation at sites in California.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study does not identify any landfill sites in California that have planned or implemented high temperature flares or flameless noncatalytic oxidation of landfill gas.

5.1.1.6 Evaluation of Benefits and Barriers

The potential benefits of implementing high-temperature flare destruction or flameless noncatalytic oxidation of LFG, in comparison with conventional LFG destruction techniques, can be summarized as follows:

Environmental Protection

- methane in LFG is almost completely oxidized, reducing greenhouse gas emissions;
- CO and NO_x emissions are in the range of 6 mg/m^3 and 70 mg/m^3, respectively;

- flameless noncatalytic oxidation units are capable of operating at very low methane concentrations without the use of additional fuel (e.g., propane); and
- high-temperature flares may be designed to continuously analyze concentrations of contaminants in the combustion chamber.

The potential for barriers that may impact the successful implementation of high-temperature flare destruction or flameless noncatalytic oxidation of LFG can be summarized as follows:

Environmental Protection

- potential users may be reluctant to attempt to deploy a technology that has not been previously approved by regulators, especially if approved technologies are readily available; and

Economic Effects

- capital cost for a foreign made flare or oxidation system may be prohibitively high.

5.1.2 LFG Conversion to Electricity

5.1.2.1 General Description

LFG can be converted to electricity through a variety of means. The most common method currently employed involves the use of internal combustion reciprocating engines coupled with a generator. Other mature technologies are gas combustion turbine engines, simple cycle steam turbines, and combined cycle plants. New technologies include microturbines and fuel cells. Gas combustion turbine engines and simple cycle steam turbines will not be discussed in this study. However, advancements in the application of internal combustion reciprocating engines and combined cycle plants will be discussed.

Internal Combustion Reciprocating Engines

Internal combustion reciprocating (IC) engines coupled with a generator ("gensets") are the most common technology used to generate electricity from LFG. Compared to other types of engines, IC engines have a lower capital cost, efficiencies on the order of 45 percent, and are reliable. However, they can be noisy and require frequent maintenance intervals. Emissions of current IC engines may limit their application in severe non-attainment areas.

Although this technology is well developed, several innovations are currently being studied that, if successful, will lead to better environmental protection and lower economic costs. The Department of Energy [2001] has initiated the Advanced Reciprocating Engines Systems (ARES) Program. Two of the goals of this program are to increase IC engines efficiency to 50 percent and to reduce nitrogen oxides (NOx) emissions to 0.1grams/horsepower-hr (g/hp-hr), which is a 95% decrease from current rates. Emerging technologies associated with the application of IC-engines include advanced sorbents for NOx control and exhaust gas recirculation.

Combined Cycle Plants

Combined-Cycle Plants utilize established technologies, and typically consist of one or more gas combustion turbines, with their hot exhaust gases being directed to heat recovery steam generators (HRSG). Pressurized steam from the HRSG is used to drive one or more steam turbine generators.

Capital costs are higher than those of simple cycle steam plants due to two different technologies being used at the same location. High operating costs are also a consideration. NOx emissions (on a lb/MMBtu basis) are similar to those of the gas combustion turbine application.

Although combined-cycle plants are not a new technology, some innovative applications and equipment have recently emerged. One new application combines LFG with natural gas to produce both thermal and electrical energy. Another innovation in combined cycle plants is the use of mobile cogeneration units. Companies such as Haase manufacture containerized cogeneration units. These individual units can produce electricity. Exhaust heat from the process can either be used, with an adsorption chiller, for refrigeration and/or air conditioning, or for heat generation. These units are delivered to the site ready-to-use; the customer needs only to supply a concrete pad foundation and gas and electricity hook-ups. The advantage to using this system is that units can be added or reduced according to changing conditions such as gas flow increase or decrease and there is no need for a building to protect the units. It is also possible to remotely monitor the units.

Microturbines

A microturbine is a small gas turbine generator that turns LFG into electricity. Microturbines are "new-comers" to LFG applications. Microturbine technology is well suited for sites that produce low LFG flow rates or have limited space for flare facilities. Microturbines will operate on LFG methane concentrations as low as 35 percent, as compared to lower operating limits of approximately 40 to 42 percent for most other technologies. The smaller units are a viable option for LFG projects where IC engines or GCT engines, (typically operating at 800 kW and 3 MW, respectively), are not an option. Microturbines can be added or removed readily as LFG volumes increase or decrease.

Compared to other engines, microturbines have lower emissions of NOx and other pollutants.

The capital cost of microturbines is currently higher than most other electricity generating technologies, but they may be somewhat less expensive to operate and maintain (O&M). For example, the microturbine manufactured by Capstone has only one moving part and does not need lubricants or coolants, which helps to lower maintenance costs. Another aspect that helps to reduce O&M is the availability of remote monitoring. A potential O&M problem for microturbines is siloxane-induced corrosion. Microturbines are more susceptible to this impact than IC engines. These units have not been in commercial service long enough to determine if this will be a major factor in O&M performance.

Fuel Cells

Fuel Cells are an emerging technology that shows great promise. A fuel cell converts LFG to electricity by extracting hydrogen from the LFG and mixing it with oxygen in a catalytic process. Individual fuel cells produce low voltages so they are typically stacked together. There are four types of fuel cells: i) Phosphoric Acid; ii) Molten Carbonate; iii) Solid Oxide; and iv) Proton Exchange Membrane. Types of fuel cells are differentiated according to the type of electrode and electrolyte used. Both the Phosphoric Acid and Proton Exchange Membrane fuel cells are low-temperature fuel cells that require a gas processing unit (GPU) to convert LFG to hydrogen-rich gas. In contrast, the Molten Carbonate and Solid Oxide are high-temperature fuel cells that do not require a GPU because the high temperatures allow the LFG to be converted to hydrogen in the fuel cell.

The most common type of fuel cell commercially available for use with LFG is the Phosphoric Acid fuel cell. Advantages of this technology include high efficiency, low emissions and minimal maintenance costs. The fuel cell must be combined with a supplemental GPU to remove sulfur and halide compounds in the LFG. The operating temperature is typically 200 degrees Celsius, and the units typically operate at 40 to 50 percent efficiency.

The Molten Carbonate fuel cell technology has not yet fully emerged in the LFG market; however, it shows great promise. This technology breaks down methane chemically into carbon dioxide and hydrogen. The advantage of using a high-temperature fuel cell is that the need for a GPU is eliminated due to conversion at high temperature (i.e., 400 degrees Celsius). The fuel cell produces electricity and high temperature heat and has the potential to run on a variety of fuels including LFG. At present, Molten Carbonate fuel cells are not economically feasible for most landfill projects and their use with LFG has been untested commercially. However, this emerging technology should be reevaluated in the future when production costs are lower.

Solid Oxide fuel cells operate at high temperature, and don't require a GPU or any catalyst. This is the least mature of the fuel cell technologies, but it offers the promise of reduced cost and larger quantities of thermal energy than the other technologies. LFG is a potential fuel source, but Solid Oxide fuel cells have not been tried for landfill applications.

The Proton Exchange Membrane (PEM) fuel cell is a low temperature technology that requires a GPU. It has not been demonstrated with LFG as a fuel source, but one company, UTC Fuel Cells, has indicated that it intends to develop a PEM fuel cell for LFG application.

Advantages of fuel cell technology include higher energy efficiencies, near zero emissions, minimum maintenance, minimum noise, high reliability, and they are available for small and large landfills. The primary disadvantage is that their capital cost is high compared to other electricity generating technologies.

Stirling Cycle Engines

The Stirling engine, invented in 1816, is an external combustion engine (i.e. the combustion process takes place outside of the piston cylinders). The cylinders contain a fixed amount of gas that is sealed inside, and motion is produced by alternate heating and cooling of this gas. There are several advantages of this technology in LFG applications.

- The engine can operate on methane concentrations as low as 30% and still achieve its rated output.
- Emissions are low. For instance, NOx emissions are approximately 0.15 grams/brake horsepower-hour (g/bhp-hr), compared with approximately 0.6 – 2.5 g/bhp-hr for a large IC engine; and uncombusted hydrocarbons approximately 0.01 pounds/megawatt-hour (lb/MWhr), compared to approximately 8.4 lb/MWhr for a large IC engine.
- Noise levels are low.
- O&M costs are reduced because the products of combustion do not corrode the precision moving parts of the engine, the corrosive effects of LFG (e.g., siloxanes) do not impact the precision parts so it is more tolerant of impurities in the LFG, and it can operate on low pressure influent (only 2 psig required), which lowers or eliminates the need for fuel compression.

Units can be combined to address a variety of flow rates, and each engine can operate on a range of flow rate and LFG quality. The capital cost is projected to be similar to IC engines (Dhungel, 2003).

5.1.2.2 Global Application of Technology and Case Histories

Internal Combustion Reciprocating Engines

Internal combustion reciprocating engines are widely used in the United States and worldwide to generate electricity from LFG. As of April 2000, approximately a third of the LFG projects in the United States were using IC engines (Thorneloe et. al., 2000). However, sites where new innovations have been implemented, including advanced sorbents for NOx control and gas recirculation, have not been identified in conjunction with this study.

Combined Cycle Plants

An example of cost-savings using co-generation technology is UCLA's installation of a system that uses a combination of LFG and natural gas to produce both thermal and electrical energy. This was done using a pair of 14.5 MW combustion turbine generators, a pair of steam generators and a condensing steam-turbine electric generator. The system, installed in 1994, produces approximately 50 MW of electricity and the thermal energy is used for heating and cooling. The payback period on initial investment was five years and UCLA cut its electricity costs by 85 percent (Spencer, 2001).

One of the largest landfills in the world, the Sudokwon landfill in South Korea, has been using containerized cogeneration units since July 2001. Currently, approximately 140,000 cubic feet of gas per hour is converted to electrical energy on the site (Haase, 2001).

Microturbines

Microturbines have been installed at the City of Burbank's Verdugo Landfill (10 units) and at the City of Los Angeles' Lopez Canyon Landfill (50 units) (Capstone, 2003). The manufacturer, Capstone, reports Lopez Canyon to hold the most microturbines installed at one site to date. The ten Capstone units installed at the City of Burbank Landfill are reported to have cost approximately $953,000 installed (or approximately $3,500,000/MW) (Wall and Bolliger, 2002). The City of Burbank received a grant from the California Energy Efficiency and Demand Reduction Program of approximately $250,000 for installation of the units. The grant made the project affordable.

Fuel Cells

A Molten Carbonate fuel cell was installed at the Michelin tire plant in Germany. The cost of the fuel cell unit was $3.9 million dollars (Geiger, 2003). The 250 kW unit produces heat and electricity for the plant. Another unit is in operation at a thermal power plant in Magdeburg, Germany. This unit provides electricity to the local power grid and thermal energy for a clinic at a nearby university (EFC, 2002). Currently, these units are operating on natural gas, but preliminary tests show that they can also operate on LFG (Bak, 2003). Typical electrical output is approximately 270 kW and thermal output is approximately 180 kW.

The USEPA [1998] conducted verification testing of a Phosphoric Acid fuel cell, using pressurized and non-pressurized LFG at the Penrose Landfill in Los Angeles, California and the Groton Landfill in Connecticut, respectively. For both projects the efficiency of the fuel cell was approximately 40 percent. In total, the fuel cell operated for approximately 700 hours at the Penrose Landfill and 5,300 hours at the Groton Landfill, and yielded a maximum power output of 165 kW and 137 kW, with an average power output of 140 kW and 120 kW, respectively (Dorn et. al., 1995).

Following on the example at Groton Landfill in Connecticut, Braintree Electric Light Department, the owner of Braintree Landfill, installed a Phosphoric Acid fuel cell to convert LFG to electricity (Raflo, 2001). The project involved installing a packaged fuel cell power plant rated for 200 kW and 480 Volts (Morley, 1999). The fuel cell supplier, one of few in the country, was UTC Fuel Cells. The total project cost was $1.7 million dollars, and was subsidized in the amount of $200,000 by the U.S. Department of Energy and $100,000 by the Massachusetts Division of Energy Resources (MDER, 1999, and MTC, 2001). Equipment capital cost was $965,000:, the GPU cost was $225,000, and the fuel cell, with installation, cost was $740,000. This yields an equipment capital cost per MW of approximately $4.8 million. Annual maintenance costs were $50,000 in 2001, or approximately $250,000 per MW. It is estimated that the owner will have to convert to natural gas after approximately five years, as the quantity of LFG will decline below the amount needed to fuel the process.

MTU CFC Solutions Gmbh, a manufacturer of Molten Carbonate fuel cells, plans to be at full scale production by 2006.

Stirling Cycle Engines

Stirling cycle engines have not been utilized in commercial LFG applications. STM Power, Inc., a U. S. based manufacturer, is planning commercial shipment of units for LFG applications by January 2004. This manufacturer reports greater than 93,000 hours of cumulative testing on the units and components.

5.1.2.3 Research Studies

Internal Combustion Reciprocating Engines

As discussed in Section 5.2.3.1, the efficiency of IC engines is being studied by the Department of Energy [2001] in their Advanced Reciprocating Engines Systems (ARES) Program. Research areas include advanced materials, unique fuel handling and processing systems, and advanced ignition and combustion systems including catalysts. The California Energy Commission's Environmentally-Preferred Advanced Generation research program includes studies for the use of advanced sorbents for NOx control and exhaust gas recirculation in IC engines.

Combined Cycle Plants

Specific research projects involving combined cycle plants, as well as specific areas needing research, have not been identified in conjunction with this study.

Microturbines

The existing microturbine projects will provide significant information regarding durability, reliability, and long-term O&M of these units in landfill applications. The answers to these questions will impact the potential for widespread application of this technology at landfills.

Fuel Cells

Verification testing of a Phosphoric Acid fuel cell was performed by the USEPA at the Penrose Landfill in Los Angeles, California (USEPA, 1998), as discussed in Section 5.1.2.2. High-temperature fuel cell technologies, Molten Carbonate and Solid Oxide, do not require a GPU, and thus may be particularly suitable to using LFG as a fuel. Testing is needed to evaluate their performance with LFG fuel. Proton Exchange Membrane fuel cells have not been used with LFG as a fuel source; however, UTC Fuel Cells has indicated that it intends to develop a PEM fuel cell for LFG application. UTC expects PEM fuel cells to be about one third the cost of Phosphoric Acid fuel cells and have superior performance. As with Molten Carbonate and Solid Oxide fuel cells, this technology will need to be evaluated to determine the performance of these technologies with LFG as the fuel source.

Stirling Cycle Engines

Commercial application of Stirling cycle engines for LFG applications is unproven. Demonstration of the utility, reliability and durability of this technology in a commercial LFG application needs to be conducted, prior to full-scale implementation of this technology at a landfill site.

5.1.2.4 Technologies in Combination

The conversion of **LFG to electricity** (as opposed to destruction by flaring) may be particularly applicable in conjunction with **waste shredding, anaerobic bioreactor landfills** and **leachate recirculation** because of the increased rate of LFG production associated with these technologies.

5.1.2.5 Application in California

All of the technologies discussed above (IC engines, combined cycle plants, microturbines and fuel cells), with the exception of Stirling cycle engines, have been deployed in California. The quantity of LFG generated is a critical factor in determining the viability of any of these technologies, and the impact of the arid climate in some portions of California on LFG generation may limit their applicability.

Air quality concerns, particularly in severe non-attainment areas, can impact the application of these conversion technologies. IC engines currently produce the highest emissions, although current initiatives to produce cleaner burning engines may improve this dramatically. Microturbines, combined cycle plants, Stirling engines and fuel cells, with their much lower emissions than other electricity generation technologies, may be more desirable in areas with significant air quality concerns.

Several California state regulations currently affect the LFG industry. Among them is the Renewables Portfolio Standard instituted by the Governor of California on 12 September 2002, which requires utilities to purchase at least 20 percent of their electricity from renewable resources (includes LFG) by the year 2017. This law was enacted on 1 January 2003 and requires an increase of 1 percent per year until the year 2017.

It is estimated that 40 million US households have access to green power programs (Vasuki, 2001). An example of a well-developed green power program is the Tennessee Valley Authority's (TVA) Green Power Switch Program. Through this program consumers can purchase 150 kW blocks (one block provides approximately 12 percent of a typical household's electricity needs) of green power for $4 per month. These blocks of electricity are produced from green power such as LFG, wind and solar technologies. The program currently extends to 6,300 residential and 300 non-residential consumers in Alabama, Kentucky, Georgia, Mississippi and Tennessee (DSIRE, 2003). Consumer surveys show that most people will pay an additional 10 percent to utilize renewable energy sources (Arner, 2002). Therefore, if green energy in the form of LFG to energy programs is made available to California, it is anticipated that many consumers may be willing to pay a small premium to receive it. However, compared to the cost of developing a LFG to energy (LFGTE) technology, this will not offset a significant amount of development cost.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study identifies several landfill sites in California that have planned or implemented landfill gas-to-electricity facilities (or are selling landfill gas for offsite conversion). These facilities include:

- Acme Landfill;

- Altamont Landfill and Resource Recovery Facility;
- Bailard Landfill;
- Central Landfill;
- City of Santa Cruz Sanitary Landfill;
- City of Palo Alto Landfill;
- Coastal / Santa Clara Landfill (Pre-1993);
- Crazy Horse Sanitary Landfill;
- Mission Canyon (Pre-1993);
- Monterey Regional Waste Management District / Monterey Peninsula Landfill;
- Olinda Alpha Sanitary Landfill;
- Otay Landfill;
- Puente Hills Landfill;
- San Marcos Landfill;
- Scholl Canyon Sanitary Landfill;
- Sycamore Sanitary Landfill;
- Tajiguas Sanitary Landfill;
- West Contra Costa Sanitary Landfill;
- West Miramar Landfill; and
- Yolo County Central Landfill.

5.1.2.6 Evaluation of Benefits and Barriers

Advantages of individual LFG to electricity technologies are presented in Section 5.1.2.1. However, some benefits are common to all LFG to electricity applications. The potential benefits of implementing LFG conversion to electricity, in comparison with conventional LFG destruction techniques, can be summarized as follows:

Environmental Protection

- allows for the beneficial re-use of a landfill by-product;
- reduces greenhouse emissions associated with destruction of LFG (standard flaring);

Economic Effects

- process may be eligible for Section 29 federal income tax credits for production of electricity from a renewable source;
- reduced emissions may generate “emissions credit” for trading;

- state requirements for utilities to purchase energy from renewable resources may be a source of revenue; and

- other economic incentives associated with the production and use of electricity from alternative sources may be available, such as below market-rate loans from the California Consumer Power and Conservation Financing Authority, loans and rebates from the Emerging Renewables Program, and incentive payments from the Renewable Energy Production Incentive (REPI) program.

Any LFG projects that utilize technologies that include a beneficial use of LFG may be eligible for incentives, as listed above. Given the rates that utilities typically pay for electricity from these type projects, incentives are frequently required for the project to be economically viable. The continued existence of several of these incentives is uncertain, and is dependent on pending federal and state legislative action.

Economic incentives for entities using LFG include rebate and loan programs, among others. The following list includes some of the available incentives, the sponsoring agency (where applicable) and sources for more information (where available):

- rebates through the Emerging Renewables Program sponsored by the California Energy Commission (CEC, 2003): http://www.energy.ca.gov/renewables/emerging_renewables.html;

- low-rate loans through the Energy Financing Industrial Development Bond Program sponsored by the California Consumer Power and Conservation Financing Authority: http://www.documents.dgs.ca.gov/CPA/IDB/App_Instructions_2003.pdf;

- emissions credits for trading to satisfy greenhouse gas regulations;

- tax credits through the federal Internal Revenue Code Section 29 for the production and sale of energy from alternative fuels;

- tax credits through the federal Internal Revenue Code Section 45 for the production and sale of electricity from closed-loop or poultry waste biomass and wind energy resources (IRS, 2002); and

- financial incentive payments through the Renewable Energy Production Incentive program sponsored by the US Department of Energy: http://www.eere.energy.gov/power/repi.html..

In addition, there are currently several bills being evaluated in congress that have the potential to affect the LFG industry. These bills propose to amend the IRC provision for producing fuel from a non-conventional source, and electricity produced from renewable sources to include LFG as a qualified energy source. Another bill may be introduced to provide tax incentives for waste-to-energy recovery products.

Barriers to the successful implementation of individual LFG to electricity technologies are presented in Section 5.1.2.1. However, some barriers are common to all LFG to electricity applications. The potential for barriers that may impact the successful implementation of LFG conversion to electricity can be summarized as follows:

Economic Effects

- capital cost of conversion plants may limit economic feasibility;

- price paid by utilities for electricity from LFGTE facilities is frequently below production cost; and
- incentives may be of limited availability and have an uncertain future.

5.1.3 LFG Use as Medium Btu Fuel

5.1.3.1 General Description

One of the simplest and most direct ways to use LFG is through direct use as a medium Btu fuel. This generally involves minimal processing (usually some gas chilling or other means of dehydration) and slight to medium pressurization for delivery. The gas may be sent by pipeline to a local customer. Common medium Btu fuel uses include industrial boiler fuel, waste-water treatment plant sludge incinerators, and steam space heat. A recent innovative use is to provide heat for greenhouses.

This technology offers a very low installed capital cost (compared to LFG-to-electricity plants) and reasonably low O&M costs. Preferably, the gas user is within one mile or less of the landfill. If the distance is greater, pipeline costs may be excessive. The most likely customer is a high volume gas user that can afford to accept and pay for all gas delivered. Medium Btu gas projects delivering to a user more than about 3.5 miles from the processing plant are generally not cost effective projects. Pipeline installation costs through heavily populated urban areas further restrict this distance.

5.1.3.2 Global Application of Technology and Case Histories

There are numerous projects that utilize LFG in some phase of greenhouse operations, including facilities in the U.S., Canada and the U.K. among others.

A recent medium Btu project will transport LFG from the City of Arlington landfill to the Fort Worth Village Creek WWTP. Renovar Energy Corporation (Renovar) acquired the LFG rights from the landfill owner, and has constructed an approximately four mile long pipeline to deliver the LFG to the WWTP. Renovar has a 20-year contract with the local utility to provide LFG to the WWTP (Renovar, 2003).

The Maxim Power Corporation in Canada is currently one of several companies developing uses for LFG in greenhouses. They are in the process of building a 5.6 megawatt LFG project in British Columbia. LFG will be used to create electricity under a 20-year agreement, to CanAgro Produce Ltd, while the heat will be used to support vegetative growth in greenhouses (James and James, 2003).

A similar scheme was used by Topgro Greenhouses Ltd., in British Columbia, where LFG was used as a fuel to supply heat and the exhaust gas, rich in carbon dioxide, was used to promote plant growth (Roe et. al, .1998). The exhaust gas contained approximately 99,000 ppm carbon dioxide. Since greenhouses generally need carbon dioxide of about 1,000 ppm, the exhaust gas was diluted (Hanson, 1995).

A group of people living in Mitchell and Yancey Counties, in the Blue Ridge Mountains of NC, formed a non-profit organization called EnergyXchange to develop a project to utilize LFG from the counties' closed landfill. EnergyXchange developed greenhouses and arts and crafts studios for local artisans that utilize the LFG for heat and energy (Nichols, 2001).

5.1.3.3 Research Studies

Specific research projects involving medium Btu applications, as well as specific areas needing research, have not been identified in conjunction with this study.

5.1.3.4 Technologies in Combination

The collection of **LFG for use as a medium Btu fuel** (as opposed to destruction by flaring) may reduce the potential environmental impact of accelerated LFG production expected with **waste shredding, anaerobic bioreactor landfills** and **leachate recirculation**.

5.1.3.5 Application in California

Utilization of LFG as a medium Btu fuel should not face significant implementation hurdles in California from either a regulatory or economic standpoint.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study identifies four landfill sites in California that have planned or implemented landfill gas medium Btu projects:

- Bradley Landfill West and West Extension;
- Cold Canyon Landfill Solid Waste Disposal Site;
- Lopez Canyon Sanitary Landfill; and
- University of California Davis Sanitary Landfill.

5.1.3.6 Evaluation of Benefits and Barriers

The potential benefits of utilizing LFG as a medium Btu fuel, in comparison with conventional LFG destruction techniques, can be summarized as follows:

Environmental Protection

- allows for the beneficial re-use of a landfill by-product;
- reduces greenhouse emissions associated with destruction of LFG (flaring);

Economic Effects

- very low installed capital cost (compared to LFG-to-electricity plants) ;
- reasonably low operations and maintenance costs because minimal processing is required;
- process may be eligible for tax credit for production of energy from alternative fuels;
- reduced emissions may generate “emissions credit” for trading;
- state requirements for utilities to purchase energy from renewable resources may be a source of revenue; and
- other economic incentives associated with the production and use of energy from alternative sources may be available.

Economic incentives are discussed in detail in Section 5.1.2.6.

The potential for barriers that may impact the utilization of LFG as a medium Btu fuel can be summarized as follows:

Economic Effects

- if the distance to the user is greater than one mile or if the pipeline would need to traverse a dense urban area, pipeline costs may be excessive.

5.1.4 LFG Conversion to High Btu Fuel

5.1.4.1 General Description

Several technologies exist to purify LFG to pipeline quality gas, which can then be sold to an industrial or commercial user of fuel trucks, buses and other vehicles, or distributed into a natural gas pipeline. These processes include brand names such as Selexol and Kryosol, and technologies such as molecular sieves, membrane separation and pressure swing absorption (PSA) units. They involve physical and/or chemical processes to remove the vast majority of the CO_2 and non-methane organic constituents from the LFG.

Selexol and PSA are the leading separation technologies currently in use. Both of these require some sort of licensing, are best suited for large LFG flows, and operate on a continuous basis with regular operator attention. Membrane separation is better suited for smaller LFG flows, and can operate with minimal operator attention. Membrane separation typically involves compressing the LFG, followed by activated carbon treatment to remove trace organics, water vapor removal, then processing through the membrane to separate the CO_2 from the LFG, leaving a gas product with a methane content of approximately 96% (Wheless et. al., 1996).

While technologies have been available for several years to generate liquefied natural gas (LNG) or compressed natural gas (CNG) from LFG, it is only recently that modifications to these existing technologies and the development of new technologies are beginning to make this process efficient enough to become economically viable. In most of the processes, pipeline quality gas is first generated from LFG using the technologies discussed above, or other newly developed technology combinations including phase separators, coalescing filters and impregnated/non-impregnated activated carbon. This gas is then converted to LNG using a cryogenic purifier process where the carbon dioxide is separated out, leaving a high grade LNG product consisting of 90%-97% methane. This LNG can be used directly as a fuel for internal combustion engines, refined to hydrogen for fuel cells, or used as a fuel for vehicles. Methane concentration for use as a vehicle fuel must be approximately 97 percent to power vehicles (Iceland Nature Conservation Association, 2001). Using an additional step, the LNG can be compressed and vaporized to make CNG, which has similar applications as LNG. LNG and CNG are cleaner burning fuels than gasoline or diesel and have been used in Europe and South Africa as vehicle fuel (Roe et. al., 1998).

5.1.4.2 Global Application of Technology and Case Histories

Waste Management, Inc. (WMI) is currently working with CryoFuel Systems to construct and operate two pilot LFG-to-LNG conversion plants at landfills in northern California. WMI expects the plants to be operational during the first quarter of 2004 (Waste Management, 2003).

The Sanitation Districts of Los Angeles County operates a plant that converts LFG from the Puente Hills landfill to CNG using membrane technology. The plant has a capacity to produce 1,000 gallons per day, but currently produces about 100 gallons per day that is used to fuel a fleet of 13 vehicles (vans and tractors). In 1992 dollars, the capital cost of this project was $1,100,000 (Wheless et. al., 1996).

Similarly, LFG is converted to CNG at the Sonzay Landfill in France where 30 small cars benefit from the technology. Each car has only the capacity to hold 21 gallons of CNG, and thus the range, 130 miles, is limited (Roe et. al., 1998). The initial cost for this project (in 1994 dollars) was $900,000, and does not include piping costs (Stahl et, al., 1993).

At a site in Iceland, LFG is upgraded and used to power vehicles. Currently, approximately 1,500 private cars are fueled by natural gas. It is estimated that Iceland can reduce its carbon dioxide emissions by 2 percent through using LNG as fuel (Iceland Nature Conservation Association, 2001).

LFG is converted to LNG at the Capital Regional District Hartland Landfill in Canada. Using only 10 to 15 percent of the collected LFG, the site generated approximately 850 gallons per day of LFG (the equivalent of 500 gallons per day of diesel fuel [Jackson, 2001]). It is expected that this landfill will provide LNG for most of British Columbia Transit's 205-bus fleet.

5.1.4.3 Research Studies

Several researchers are currently working on an alternative method to cryogenic purification to produce LNG. This new technology uses ultra-sound to liquefy methane. One of the first sites to investigate this technology was Enderby Quarry Landfill in the United Kingdom. At this site, a plant produced 400 gallons per day of liquid methane (Eden, 2001).

Additional research is being conducted to develop small conversion units for application at small landfill sites by CryoFuel Systems.

5.1.4.4 Technologies in Combination

The **conversion of LFG to a high Btu fuel** (as opposed to destruction by flaring) may be particularly applicable in conjunction with **waste shredding, anaerobic bioreactor landfills** and **leachate recirculation** because of the increased rate of LFG production associated with these technologies.

5.1.4.5 Application in California

Revenue opportunities for this technology in California are limited by the California Health and Safety Code Section 25420 and Section 2775.6 of the Public Utilities Code. These codes require every person furnishing LFG offsite to a gas pipeline or supplier to sample and test twice a month for chemicals known to cause cancer or reproductive toxicity pursuant to specified test guidelines. Given the potential liability associated with distributing purified LFG that contains these type chemicals, it becomes an almost de facto requirement to remove these chemicals to undetectable levels. The cost to remove vinyl chloride (present in most LFG) to undetectable levels is prohibitively expensive. Therefore high Btu gas derived from LFG is generally limited to CNG or LNG for vehicle fuel or industrial applications, or methanol for industrial applications. All of these alternatives involve additional process equipment and some form of product distribution network to complete a business transaction.

One of the obstacles to widespread utilization of LNG as a vehicle fuel is the lower Btu value of LNG compared to diesel fuel. One gallon of LNG is approximately equivalent in Btu value to 0.6 gallon of diesel, therefore requiring more LNG than diesel fuel to travel the same distance. For some applications, this will require a LNG-powered vehicle to have larger fuel carrying capacity. For applications such as refuse trucks, this problem may be overcome by installing the LFG-to-LNG conversion plant and fueling station at the landfill itself.

It is anticipated that there will be an increased demand for natural gas in the future. This increase would positively affect the LFG industry. Many cities are investing in the technology for their transportation systems. For example, the Port of Seattle operates light- and heavy-duty natural gas vehicles, which have lower maintenance costs and lower greenhouse gas emissions than gasoline vehicles. Also, Washington State offers a state fuel tax incentive for CNG vehicles. These types of benefits along with the increased use of natural gas vehicles suggest the potential for a growing trend in the LFG-to-LNG industry.

The California South Coast Air Quality Management District (SCAQMD) has enacted the 1190 Series fleet rules that establish requirements for fleet operators to upgrade their fleets to vehicles with lower emissions than currently operating. This may increase the demand for cleaner burning fuels such as LNG or CNG, which in turn may improve the economic viability for LFG-to-LNG conversion projects.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study identifies three landfill sites in California that have planned or implemented landfill gas high Btu projects:

- Chicago Grade Landfill;
- Puente Hills Landfill; and
- South Chollas Landfill (Pre-1993).

5.1.4.6 Evaluation of Benefits and Barriers

The potential benefits of converting LFG to High Btu fuel, in comparison with conventional LFG destruction techniques, can be summarized as follows:

Environmental Protection

- allows for the beneficial re-use of a landfill by-product;
- reduces greenhouse emissions associated with destruction of LFG (flaring);
- most applicable to landfills with high LFG production;
- new research in the area of smaller conversion units may allow this technology to be applied to low LFG production sites as well;
- LNG and CNG are cleaner burning fuels than gasoline or diesel;
- light- and heavy-duty natural gas vehicles produce lower greenhouse gas emissions than gasoline vehicles;

Economic Effects

- an anticipated increase in demand for natural gas will make the process more economically viable;
- light- and heavy-duty natural gas vehicles have lower maintenance costs;
- fuel tax incentives may be available for CNG vehicles;
- reduced emissions may generate “emissions credit” for trading; and

Other Effects

- LNG/CNG fuel may be utilized on-site by landfill and waste collection vehicles, where vehicles return daily to the same location for fueling;

The potential for barriers that may impact the successful conversion of LFG to High Btu fuel can be summarized as follows:

Economic Effects

- high capital costs;
- gas purification technologies must be employed to convert LFG to LNG, and are currently expensive;
- conversion process involves additional equipment and some form of product distribution network;
- volatility of the natural gas market makes revenue from sale of the fuel product unreliable;

Other Issues

- regulatory constraints in California may limit offsite distribution;
- application of product fuel generally limited to CNG or LNG for vehicle fuel or industrial applications, or methanol for industrial applications;
- the lower Btu value of LNG (compared to diesel) limits widespread utilization of LNG, since a higher volume of fuel is required to produce the same amount of energy;
- limited driving range of CNG fueled vehicles makes them a less attractive option for consumers; and
- limited availability of LNG/CNG fueling stations makes them a less attractive option for consumers.

5.1.5 LFG Use in Leachate Evaporation

5.1.5.1 General Description

Specialized boiler or evaporative devices use LFG as a fuel to evaporate leachate, condensate and/or contaminated groundwater and to thermally destroy the vaporized contaminants in the LFG flare. Alternatively, for smaller volumes of liquid flow, technologies exist to inject the leachate or condensate directly into the flare using an atomizing spray nozzle.

Assuming LFG has a 50 percent methane content, about 22 to 25 cubic feet of LFG are required to evaporate 1 gallon of landfill liquid (leachate, condensate, and/or groundwater). If the resulting vapor is routed to the flare for thermal destruction of the volatile compounds in the vapor, an additional 70 to 75 cubic feet of LFG is required to complete this task. Therefore, about 100 cubic feet of LFG is consumed in evaporative management of 1 gallon of landfill liquid.

For low volume flows (typically 1 to 2 gpm, but no more than about 5 gpm) the low cost option involves injecting the leachate/condensate directly into the flame in the flare through an atomizing spray nozzle. Cost of such units, with ancillary equipment, is $50,000 to $100,000.

5.1.5.2 Global Application of Technology and Case Histories

WMI has deployed a leachate evaporator unit at its Olympic View Sanitary Landfill in Port Orchard, Washington. The system treats approximately 20,000 gpd of leachate using LFG as the fuel (Shaw EMCON/OWT, 2003).

WMI has installed 12 leachate evaporators at landfills in Texas (Waste Management, 2003).

A direct leachate injection process was installed at the Loraine County 1 Landfill in northern Ohio. This system injects approximately 2 gpm of leachate into the modified enclosed LFG flare. No published information discussing this project was reviewed in conjunction with this study, and performance of the system has not been reported.

5.1.5.3 Research Studies

Specific research projects involving the use of LFG for leachate evaporation, as well as specific areas needing research, have not been identified in conjunction with this study.

To fully evaluate the suitability of LFG for leachate evaporation at a particular site, further evaluation of experiences at existing sites is recommended.

5.1.5.4 Technologies in Combination

Leachate recirculation and anaerobic bioreactors typically reduce the volume of leachate that needs to be treated. Since **direct flare injection and evaporation technologies** manage lower leachate volume flows, these technologies may be very suitable for application in conjunction with **leachate recirculation** and **anaerobic bioreactors,** where a portion of the leachate is reserved for recirculation. In addition, **leachate evaporation** may be appropriate for landfill sites where the waste has undergone **biological pre-treatment,** such that less leachate is expected after disposal.

5.1.5.5 *Application in California*

Direct flare injection technology is not universally accepted and could be a permitting challenge in southern California due to non-attainment area conditions. Permitting might be difficult because combustion is not complete, and some volatiles (e.g. vinyl chloride) and metals may be present in emissions.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study does not identify any landfill sites in California that have planned or used LFG for the evaporation of leachate.

5.1.5.6 Evaluation of Benefits and Barriers

The potential benefits of using LFG for leachate evaporation, in comparison with conventional LFG destruction techniques, can be summarized as follows:

Environmental Protection

- allows for the beneficial re-use of a landfill byproduct;
- may reduce the impact of handling and disposing leachate;

Economic Effects

- may reduce costs associated with leachate disposal;
- qualifies for federal tax credits when LFG is the fuel; and

Other Effects

- most applicable to landfills with lower leachate treatment needs.

The potential for barriers that may impact the successful utilization of LFG for leachate evaporation can be summarized as follows:

Environmental Protection

- incomplete combustion with the direct flare injection process may result in emission of volatiles and metals; and

Other Issues

- application in California may be limited by permitting issues.

5.1.6 LFG Conversion to Industrial Products

5.1.6.1 General Description

The CO_2 in LFG (approximately 50% by volume) can be extracted and used for industrial purposes. Uses of industrial grade carbon dioxide include liquid or solid dry ice, greenhouse environment enhancement, and for pH correction in wastewater treatment plants. The most costly step in this process is contaminant removal. Options for contaminant removal include solvent extraction, cryogenic separation, use of membranes, and use of proprietary technologies such as Acrion's CO_2 Wash system.

Acrion's CO_2 Wash process, using cold liquid carbon dioxide to recover and purify LFG, serves several purposes. Atmospheric emissions of methane are reduced. A portion of the carbon dioxide in LFG is captured for use as a carbon source in the methanol synthesis gas, further reducing greenhouse gas emissions. LFG contaminants are captured in a relatively small stream of carbon dioxide that permits efficient contaminant destruction by incineration (Cook et al., 1997). This process yields pipeline quality methane and carbon dioxide.

Advantages to systems such as CO_2 Wash are the reuse of carbon dioxide in LFG as a solvent, and the separation of methane and carbon dioxide is performed in one compression step (Neyman, 2003). Due to the high capital cost, for a process like this to be economically feasible there must be a continuous supply of LFG for at least ten to fifteen years.

Methane and CO_2 from LFG can be synthesized to methanol, another valuable industrial chemical. While technology to make methanol from LFG has been available for several years, it has not been commercially viable. Acrion recently partnered with Alcohol Solutions of St. Louis and developed a commercially viable process for methanol synthesis from LFG. Acrion's CO_2 Wash process can be adjusted to efficiently produce gas containing methane and CO_2 in the desired ratio (about 2.3 methane:1 CO_2) as a feedstock for methanol synthesis. Using this process, LFG methane is recovered locally as methanol, a commodity chemical easy to store, transport and distribute. The first plant has recently been constructed at a landfill in Columbus, Ohio.

Conversion of LFG to hydrogen is not currently a commercially available or economically feasible option. However, using the Underoxidized Burner (UOB^{TM}) process to generate hydrogen though a process involving partial oxidation, it is possible to convert LFG to usable hydrogen (Lelewer, 1999).

5.1.6.2 Global Application of Technology and Case Histories

Acrion has completed two tests on their CO_2 Wash contaminant removal system. The first was in Al Turi Landfill in New York, where their contaminant removal system was placed in a 700 kW generator (Brown, 2002). The final product was used as fuel in fuel cells. Another test was performed at EcoComplex in New Jersey, where LFG was converted to carbon dioxide to be used in greenhouses and fuel to be used for electricity generation.

5.1.6.3 Research Studies

None of these industrial technologies have had significant commercial scale demonstration, and some are still in development. The economic viability of these technologies should be demonstrated in commercial applications prior to widespread application at landfill sites.

5.1.6.4 Technologies in Combination

The **conversion of LFG to industrial products** (as opposed to destruction by flaring may be particularly applicable in conjunction with **waste shredding, anaerobic bioreactor landfills** and **leachate recirculation** because of the increased rate of LFG production associated with these technologies.

Technologies that convert LFG to LNG and CNG must separate methane from CO_2. Processes that do this most efficiently will be more cost effective, and the separated CO_2 can be used as an industrial product. Combining processes that efficiently separate CO_2 from the LFG with processes that convert LFG to LNG or CNG may improve cost efficiency.

5.1.6.5 Application in California

Given the low emissions of these technologies, especially of green house gases, these technologies should not face significant application hurdles in California.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study does not identify any landfill sites in California that have planned or implemented the conversion of LFG to industrial products.

5.1.6.6 Evaluation of Benefits and Barriers

The potential benefits of converting LFG to industrial products, in comparison with conventional LFG destruction techniques, can be summarized as follows:

Environmental Protection

- allows for the beneficial re-use of a landfill by-product in the form of carbon dioxide and methanol;
- reduces greenhouse emissions associated with destruction of LFG (flaring); and

Economic Effects

- the sale of products will generate additional/offsetting revenue to the landfill.

The potential for barriers that may impact the successful conversion of LFG to industrial products can be summarized as follows:

Economic Effects

- to be economically feasible, requires continuous supply of LFG for 10 to 15 years;
- conversion to hydrogen is currently prohibitively expensive; and
- markets for products must be available.

5.2 Passive Aeration

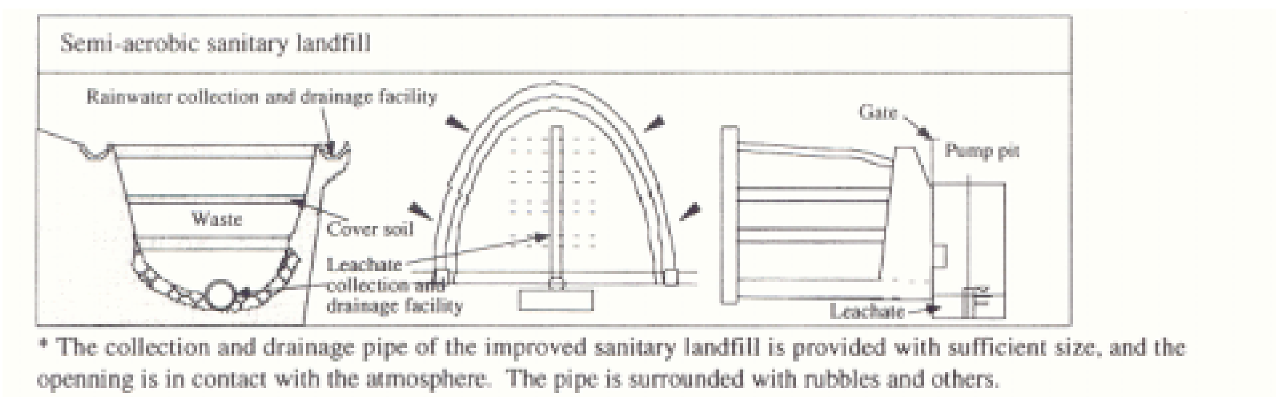
Passive aeration is a method of developing a semi-aerobic landfill condition within a (new or existing) landfill to enhance waste degradation. Under semi-aerobic conditions, degradation of the waste mass has been found to occur more rapidly than under the anaerobic conditions of a typical landfill or anaerobic bioreactor landfill (Hudgins, 2001; Stessel, 1992). With passive aeration the waste mass is exposed to air under ambient conditions. Passive aeration provides a more cost-effective alternative than active air injection, discussed in Section 5.3, due to the energy requirements of forcing air into the waste mass. However, passive aeration may have more limited beneficial results than air injection because only the waste immediately surrounding the passive aeration system may be affected.

Passive aeration technology enhances the degradation of waste prior to closure of the landfill, thereby reducing degradation potential of the material following closure and likewise reducing the long-term risk to the environment.

5.2.1 General Description

The method of passive aeration that has been implemented most extensively is known as the "Fukuoka Method", developed at Fukuoka University, Japan. This method utilizes the leachate collection and recovery system (LCRS) for passive aeration. In the Fukuoka Method the LCRS pipes have a dual purpose. Leachate flows out of the landfill in the LCRS pipes, but only in the bottom half of the pipe. Air is thus introduced to the landfill through the upper half of the LCRS pipes. The LCRS pipes are vented to the atmosphere, resulting in a thermodynamic condition that allows the circulation of air through the pipes due to the difference between the temperature of the waste mass and the ambient temperature outside the landfill (Hanashima, 1999). The vent pipe is installed vertically and connects perpendicularly to the LCRS system, facilitating the circulation of air in the landfill. A schematic of a typical passive aeration system using the Fukuoka Method is provided in Figure 5.1.

Figure 5.1: A Passive Aeration System **Source: Hanashima, 1999**



5.2.2 Detailed Description and Process Options

To evaluate the applicability of a passive aeration system to a (new or) existing landfill, consideration must be given to various characteristics and procedures that will vary from typical landfill characteristics and standard landfilling procedures as practiced in the U.S. In particular, consideration must be given to:

- waste and site climate characteristics;

- LCRS design; and
- the emissions monitoring system.

It should be recognized that the installation of a passive aeration system does not eliminate the need for a gas extraction system. Because the aeration system is passive, anaerobic degradation will continue to occur in areas of the landfill where oxygen does not infiltrate, producing landfill gases (i.e., methane) that need to be controlled.

5.2.2.1 Waste and Site Climate Characteristics

Passive aeration is most applicable to wastes with low density and high organic content. Low waste density allows increased diffusion of air into the waste mass.

For application at an existing landfill, the level of degradation of the waste mass should be considered. For very old landfills, the level of degradation already achieved may diminish the effectiveness of a passive aeration system.

The in-situ moisture content of the waste mass is affected by the waste type and site climatic conditions. Moisture content of the waste mass should be considered for two reasons. First, the presence of liquid in the waste enhances degradation under anaerobic conditions, as described in Section 4.1, Anaerobic Bioreactor, and Section 5.4, Leachate Recirculation. Second, exposure to oxygen during degradation increases the internal temperature of the waste, such that the presence of moisture in the waste helps to control the temperature of the waste mass.

Because the performance of a semi-aerobic passive aeration system is governed by moisture in the waste mass in addition to the extent of aeration, this technology may be more applicable to sites that have the following characteristics:

- sites in areas with rainy climates;
- sites with high moisture content wastes; or
- sites where anaerobic bioreactor technology or leachate recirculation/liquid injection technology are also being implemented.

5.2.2.2 LCRS

A key component in the success of a passive aeration system is the ability of the LCRS to accommodate air circulation as well as the volume of leachate generated. If the LCRS piping does not have sufficient capacity to allow leachate to flow only in the bottom half of the pipes, air circulation in the upper half of the pipes will be reduced.

In addition, evaluation of an existing LCRS (or design of a new LCRS) should consider the susceptibility of the system to biological clogging. Existing studies suggest that the LCRS of a semi-aerobic landfill system may be particularly susceptible to biological clogging (Cossu, 2001). The compatibility of the LCRS with the chemical and biological make-up of site-specific leachate under aerobic conditions with respect to minimization of clogging potential is an important consideration during design of the passive aeration system.

5.2.2.3 Emissions Monitoring System

The design of a passive aeration system using the Fukuoka Method allows for the circulation of air into the waste mass and ventilation to the atmosphere. Although, the aerobic degradation process promoted by the passive aeration system results in the generation of carbon dioxide in lieu of typical landfill gases such as methane, the continuous ventilation of the system may result in the unexpected release to the atmosphere of landfill gases (which will continue to be generated in areas of the landfill not affected by the passive aeration system). Therefore, as in all MSW landfills, a landfill gas monitoring program should be established and should include monitoring of the passive aeration ventilation system.

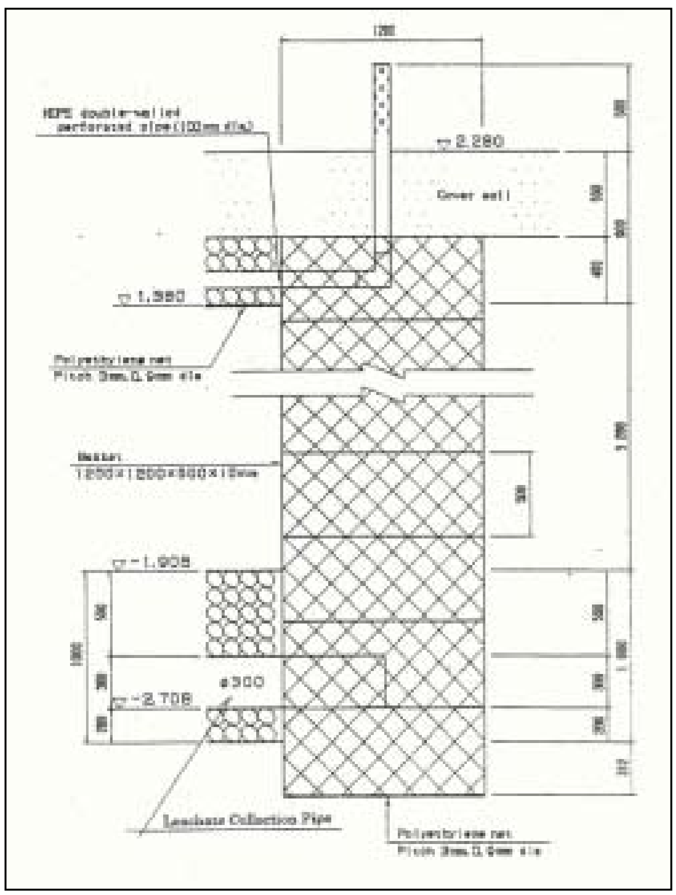
5.2.3 Global Application of Technology and Case Histories

Passive aeration technology, using the "Fukuoka Method", has been applied extensively in Japan, where accelerated degradation is very important (to allow land reclamation) and the rainy climate enhances the effectiveness of the method. Passive aeration has also been applied at sites in Malaysia and Iran, but no cases of application in Europe or the U.S. have been identified.

The Fukuoka Method was implemented in conjunction with a leachate recirculation system to rehabilitate and remediate the Yamato Kantaku Landfill (Japan) and to allow the placement of additional waste at the site. The passive aeration system that was designed and implemented at the site is described as follows.

"Vertical ventilation pipes were installed to exhaust the generated gases from the landfill, and facilitate the intake of fresh air into the waste layers. These ventilation pipes were installed by stacking metal cages, called 'futon kago', filled with pebbles. The vertical ventilation pipes run the full depth of the landfill, from the bottom of the waste layers to the surface. At the base they are connected to the leachate collection pipes" as shown in Figure 5.2 (Matsufuji, 2001).

Figure 5.2: Vertical Gas Venting Facility **Source: Matsufuji, 2001**



5.2.4 Research Studies

Laboratory and field-scale studies have been performed or are ongoing to evaluate the performance and characteristics of passive aeration technology. In particular, areas of research that have been studied to date and that were identified in conjunction with this report include the following (Hanashima, 1999; Cossu, 2001):

- effects of passive aeration on biogas and leachate generation and composition;
- comparative evaluation of aerobic degradation, anaerobic degradation and waste pre-treatment methods; and
- quantification and optimization of air flow for aerobic degradation.

Because full-scale trials of passive aeration has been limited to Asia, additional research is recommended on the applicability of passive aeration technology to the waste characteristics and climatic conditions of Europe and North America.

5.2.5 Technologies in Combination

To achieve proper moisture conditions within the landfill, lower temperatures and enhance degradation, **leachate recirculation** may be used in conjunction with **passive aeration** for remediation of an existing landfill / landfill cell.

Use of **an exposed geomembrane cover system** or a **phytoremediation cover system** may not be applicable in conjunction with some technologies for enhanced degradation of the waste such as **leachate recirculation, air injection** or **passive aeration**. The build-up of landfill gas under these types of cover systems is detrimental to their effectiveness.

5.2.6 Application in California

Passive aeration technology using the Fukuoka Method (Hanashima, 1999) has been implemented in Japan and other Asian countries, primarily in areas where heavy rains increase the moisture content of the waste. This technology has not yet been tried in North America or Europe. It may be applicable in parts of Northern California, where the climate is similar to some parts of Japan. There are no regulatory barriers to implementation of this technology in California. However, some air district landfill gas rules that were modeled after the Air Resources Board’s Technical Guidance for implementing 40 Code of Federal Regulations Part 60, may prohibit the passive venting of landfills directly to the atmosphere.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study does not identify any landfill sites in California that have planned or implemented passive aeration technology.

5.2.7 Evaluation of Benefits and Barriers

The potential benefits of implementing passive aeration technology, in comparison with conventional MSW landfilling techniques, can be summarized as follows (Hanashima, 1999; Cossu, 2001):

Environmental Protection

- reduced generation of methane due to aerobic degradation of waste;
- improved performance of the final cover system due to accelerated stabilization of waste;

- decrease in long-term environmental risk due to accelerated stabilization of the waste mass;

Economic Effects

- low up-front capital expenditure, since existing LCRS system may be utilized for circulation of air;
- low operations and maintenance costs, since passive aeration incorporates no mechanical systems;
- increased air space due to enhanced degradation of waste; and

Other Issues

- requires no changes to Subtitle D landfill regulations.

The potential for barriers that may impact the successful implementation of passive aeration technology can be summarized as follows:

Environmental Protection

- insufficient moisture in the waste mass may result in high temperatures and landfill fires if moisture is not properly monitored and controlled;
- LCRS using passive aeration may be susceptible to biological clogging, reducing the ability to control head on the liner;

Other Issues

- technology may not be applicable to all sites, based on site climate, moisture characteristics of waste, organic content of waste, waste density, and configuration and capacity of existing LCRS; and
- passive aeration is untried in areas where waste characteristics and climatic conditions are similar to expected conditions in California.

5.3 Air Injection

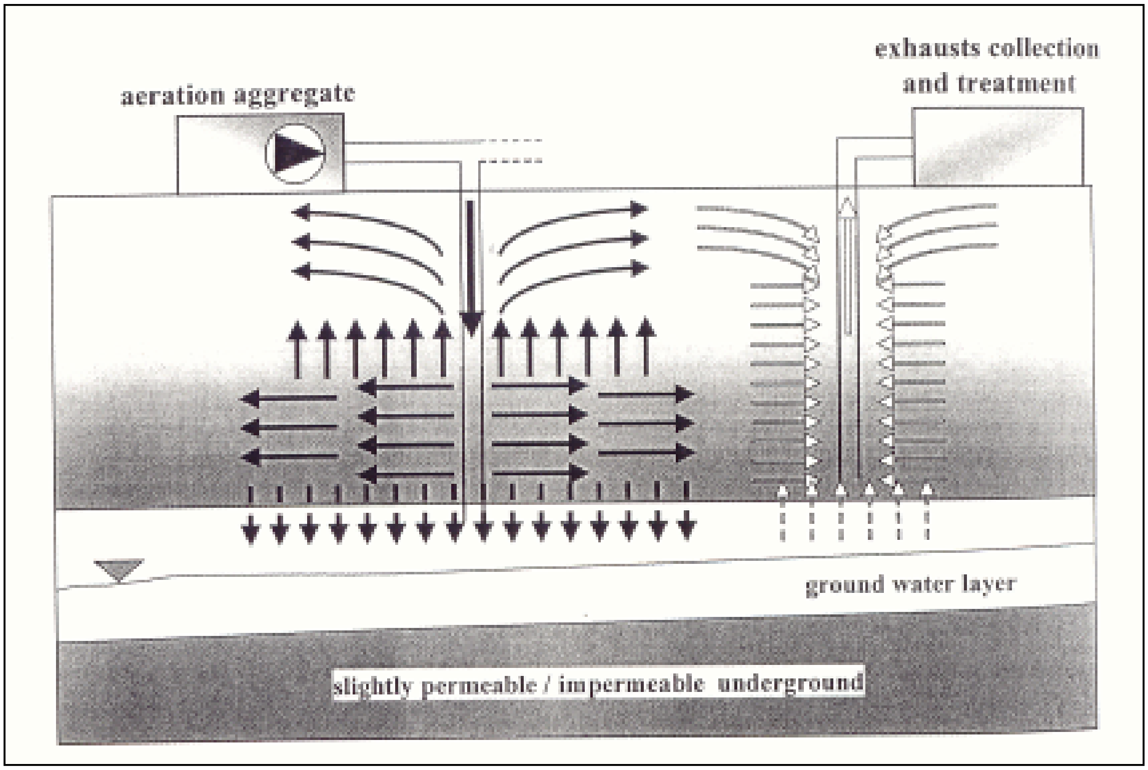
Air injection is an active method of developing an aerobic landfill condition within an existing landfill, though the method may also be applied to a new landfill. Under aerobic conditions, the biodegradable mass is converted to mostly carbon dioxide and water, with a significant reduction in harmful landfill gases as well as a potential for the reduction of VOCs in leachate (Hudgins, 1999). In addition, degradation of the waste mass has been found to occur more rapidly under aerobic conditions than under the anaerobic conditions in a typical landfill or anaerobic bioreactor landfill (Hudgins, 2001; Stessel, 1992). Air injection technology can enhance the degradation of waste prior to closure of the landfill, thereby reducing degradation potential of the material following closure and likewise reducing the long-term risk to the environment. It also can be used at older closed sites for similar purposes.

Using air injection, the waste mass is exposed to air under pressure through the use of horizontal or vertical injection wells. The level of degradation achieved is dependent on the rate and quantity of air injected. The excess gas is extracted from the landfill through wells, similar to a typical gas collection system.

5.3.1 General Description

The primary components of an air injection waste remediation scheme include the air injection system, the gas collection system, and the emissions monitoring system. Air injection is generally performed using vertical or horizontal wells distributed across the landfill area. Horizontal wells are typically used only in the construction of a new landfill, while vertical wells may be used at either a new or existing landfill. The general concept of air injection is depicted in Figure 5.3 with "aeration aggregate" representing the air injection system and "exhausts collection and treatment" representing the gas collection system:

Figure 5.3: An Air Injection System **Source: Heyer, 2001**



Because the volume of landfill gas that needs to be collected increases with air injection, a higher capacity gas collection system is typically installed in conjunction with the installation of the air injection system than would be installed in a comparable MSW landfill without an air injection system.

Although proper design of an air injection system should not result in an increased potential for uncontrolled emissions, the development of a comprehensive emissions monitoring system is recommended to verify performance of the landfill containment and control systems.

5.3.2 Detailed Description and Process Options

To evaluate the applicability of an air injection system to a new or existing landfill, consideration must be given to various characteristics and procedures that will vary from typical landfill characteristics and standard landfilling procedures as practiced in the U.S. In particular, consideration must be given to:

- waste and site characteristics;
- air injection system configuration and capacity;

- gas collection system capacity;
- LCRS design; and
- extent of emissions monitoring system.

5.3.2.1 Waste and Site Climate Characteristics

Air injection is most applicable to homogeneous wastes with low density and high organic content. Homogeneity allows more even distribution of air through the waste mass, and thus more even degradation. Low waste density allows increased penetration of air into the waste mass and decreased energy requirements.

For application at an existing landfill, the level of degradation of the waste mass prior to system installation should be considered. For very old landfills, the level of degradation already achieved may limit the effectiveness of an air injection system.

The in-situ moisture content of the waste mass is affected by the waste type and site climatic conditions. Moisture content of the waste mass should be considered for two reasons. First, exposure to oxygen during degradation increases the internal temperature of the waste to temperatures as high as 175º F (80º C), such that the presence of moisture in the waste helps to control the temperature of the waste mass and minimize the risk for landfill fires. Second, the presence of liquid in the waste enhances degradation under anaerobic conditions in areas not penetrated by air injection, by keeping the temperature in these areas in the mesophilic range of 60 to 104ºF (15 to 40 ºC) (Hudgins, 1999).

Because the performance of an air injection system is governed by moisture in the waste mass in addition to the air injection rate, this technology may be more applicable to sites that have the following characteristics:

- sites in areas with rainy climates;
- sites with high moisture content wastes; or
- sites where anaerobic bioreactor technology or leachate recirculation/liquid injection technology are also being implemented.

Other site limitations that should be considered include cell size and waste placement procedures. Large cells are generally more heterogeneous in nature than small cells. The use of low permeability daily and intermediate cover materials may limit the penetration of air and the overall effectiveness of the air injection system.

5.3.2.2 Air Injection System

Air compressors or electric blowers are generally used to force air into the waste at a controlled rate (Hudgins, 2001). Air is distributed through the waste mass by convection and dispersion, creating an aerobic condition (Heyer, 2001). The distribution of air injection wells through the landfill is evaluated on a site-specific basis.

The air injection rate should be evaluated on a case-by-case basis to optimize degradation. The optimal injection flow rate will provide the proper amount of oxygen to sustain the resident microbe population. One study has found that the optimal injection rate for MSW is 8 standard cubic feet per minute per cubic yard of waste at 59ºF (5 liters per minute per cubic meter of waste at 15º C) (Hanashima, 1999). However, due to the high energy cost of injecting air, air is often injected at a rate below optimum.

The required duration of air injection to achieve a site-specific goal for stabilization of the waste mass will vary depending on the characteristics of the site and the waste mass, as well as the rate of injection and well spacing. One case study reports a injection duration of two years to achieve degradation which would otherwise have occurred over many years or decades (Heyer, 2001).

To minimize the risk for uncontrolled emissions of landfill gas, an intermediate cover is typically installed over the waste mass prior to initiating injection (Hudgins, 2001). Additional precautions may also be taken to minimize the risk of emissions through portions of the landfill not being treated, and to minimize the risk of explosion from improper mixing of methane and oxygen.

5.3.2.3 Gas Collection System

The collection of landfill gas generated by an air injection system may be performed in two ways. A system of dedicated gas collection wells may be installed during construction of the air injection system, similar to the gas collection systems typically at closure of an MSW landfill, but with increased capacity. Alternatively, the air injection system may be configured such that the air injection wells may also function as gas extraction wells. In this way, localized portions of the landfill may be treated independently and the system may be optimized for varying conditions across the site.

5.3.2.4 LCRS

Theoretically, the aerobic degradation process produces liquid as a by-product. However, in practice no record of an increase in leachate production under the aerobic degradation conditions generated by the air injection process has been identified. This may be due to the high temperatures expected within the landfill body. Because aerobic degradation does generate liquid and because the implementation of air injection may be accompanied by the injection of liquid for temperature control, as discussed previously, the capacity of the LCRS should be carefully considered during design of the air injection system.

5.3.2.5 Emissions Monitoring System

The accelerated gas generation caused by air injection is expected to result in increased degradation during the life of the landfill and a shortened post-closure care period. Therefore, monitoring of emissions at the landfill during its active life should be enhanced. Monitoring programs should include groundwater quality, surface water quality and air quality. In addition landfill gas, leachate, and waste characteristics may be monitored to optimize performance of the air injection system.

Although a properly design landfill gas extraction system for an aerobic landfill should be as effective if not more effective than the system design for a traditional MSW landfill, the increased and accelerated production of landfill gas results in an increased concern for uncontrolled emissions, especially prior to final closure. Therefore, as in any landfill, a landfill gas monitoring program should be established during filling to monitor the performance of the landfill gas extraction system.

5.3.3 Global Application of Technology and Case Histories

Pilot studies of the application of air injection technology as a method of remediating existing landfills have been performed in Italy and Germany. Furthermore, three sites have been identified in the United States where air injection has been incorporated into the design of new landfills, as identified in Section 4.2 of this report.

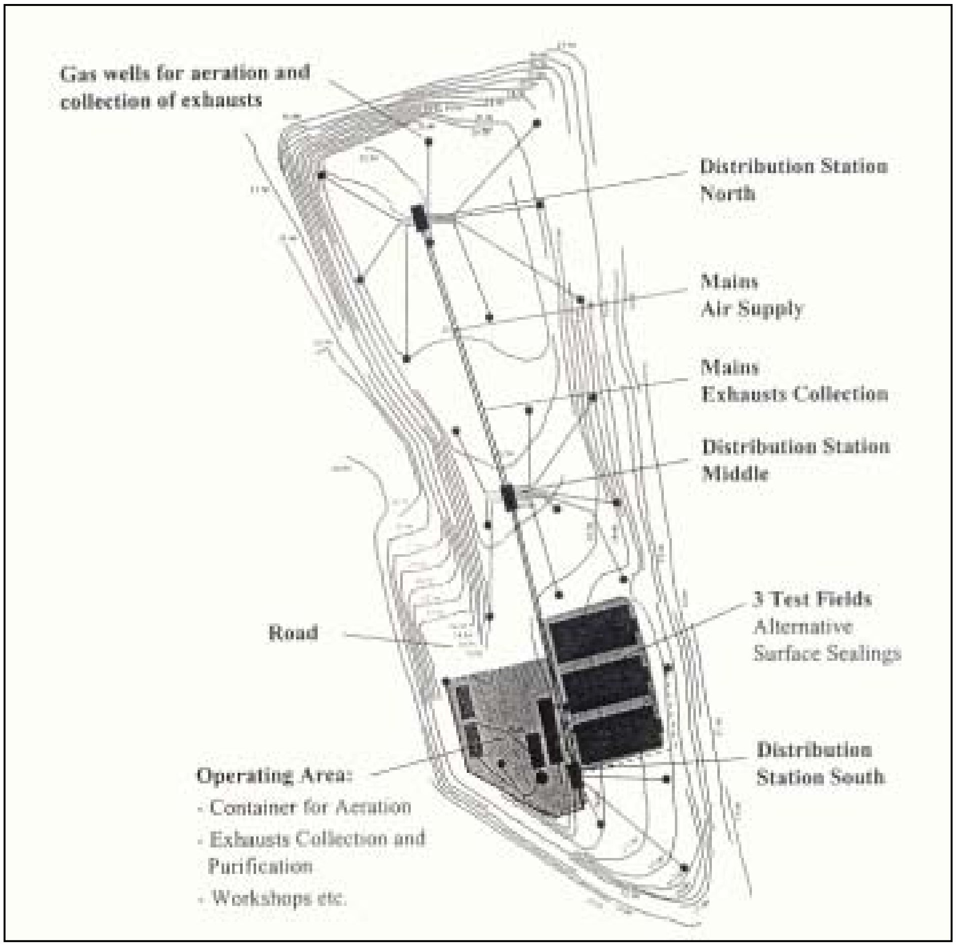
At a site in Kuhstedt, Germany, air injection technology has been applied to the remediation of an "old" unlined landfill. Due to the potential for risk to environment from the unlined landfill, air injection technology with an alternative cover system was selected to achieve the following goals:

- lower cost associated with surface-sealing through the use of an alternative cover system;
- lower cost associated with groundwater remediation than traditional methods;
- lower cost associated with leachate purification, especially when used in conjunction with leachate recirculation;
- shorter gas emissions period;
- shorter aftercare period; and
- earlier site re-use with wider options for re-use (Heyer, 2001).

The following excerpt from Heyer (2001) describes the technical concept of the air injection system and provides details of the system components.

"The **basic technical conception** of the aeration of a whole landfill body consists of a system of gas wells, through which atmospheric oxygen is led into the landfill body via active aeration in such a way that an accelerated aerobic stabilization of deposited waste is realized. At the same time, the low-contaminated waste gas is collected and treated in a controlled way by means of further gas wells. Aeration is effected with low pressures and is continuously adjusted to oxygen demand so that energy consumption is low and constantly optimized." The layout of the air injection system is shown in Figure 5.4.

Figure 5.4: Layout of an Air Injection System **Source: Heyer, 2001**



"Each of the 25 **gas wells** is connected to a distribution station by means of separate mains. There, the mains can be connected to the distribution system for aeration or to the system for the collection of waste gas.

"Aeration via the gas wells: aerobization of the area of influence of each gas well is guaranteed by the adjusted excess pressure respectively by the added air volume.

"Waste gas collection via the gas wells: By means of adjusted negative pressure, waste gas is continuously sucked within the area of influence of the gas well so that uncontrolled waste gas emissions via landfill surface respectively gas migration via soil vapor path into the neighboring subsoil are kept at a low and acceptable level.

"**Separate mains** connect the gas wells to the distribution station for the distribution of added air respectively for gas collection. The installation of the separate mains took place on the existing provisional surface covering. Uneven spots were adjusted when required and a planum was produced to serve as location route. They were installed with a continuous slope and covered with 30 cm of soil material.

"Three **distribution stations** allow the connection of the separate mains to the main aeration ducts (air supply) and with the main gas extraction line (waste gas collection for a waste gas treatment). Furthermore, they include armatures (valves, ball stop-cocks etc.) for each separate main and for the trunk mains for supervision and control."

“The **distribution network for aeration** is connected with the compressing unit for aeration by the main supply duct. The **gas collection system for the collection of waste gas** is provided with a condensate separator and connected to the compacting unit for the collection of waste gas by the main suction duct.

“Compressing unit for aeration and collection of waste gas: Design and operation of the aeration- and waste gas collection devices are chosen in such a way that, under normal automated operation, no explosive atmospheres are to be expected on the waste gas side, [and] a high level of utilization of the added oxygen is achieved - meaning that oxygen concentration is low in the waste gas. All compressing units for aeration and waste gas collection – including switchboxes and control devices – were installed in a mobile container.

“Waste gas cleaning: As a matter of principle, the contaminated waste gas can be purified by means of biowashers and biofilters or by adsorption on activated carbon and by noncatalytic autothermic methods.”

Construction of this system was completed in Spring 2001. Preliminary monitoring results from the first 40 days of operation of the system suggest that aerobic biodegradation is occurring and that stabilization of the waste mass has been accelerated. The anticipated duration of air injection has not been identified, but based on similar projects is expected to be on the order of two years.

5.3.4 Research Studies

Laboratory and field-scale studies have been performed or are ongoing to evaluate the performance and characteristics of air injection technology. In particular, areas of research that have been studied to date and that were identified in conjunction with this report include the following (Hudgins, 1999; Cossu, 2001; Ritzkowski, 2001):

- effects of air injection on biogas and leachate generation and composition;
- comparative evaluation of aerobic degradation, anaerobic degradation and waste pre-treatment methods;
- evaluation of degradation rates using aerobic techniques; and
- quantification and optimization of air flow for aerobic degradation.

Additional full-scale implementation of air injection, as well as pilot studies, is expected to come on-line at various sites in the near future (including one site in Florida). As more sites come on line, additional data will be available regarding construction experiences, cost, operational experiences and environmental risk / benefits.

5.3.5 Technologies in Combination

Use of **an exposed geomembrane cover system** or a **phytoremediation cover system** may not be applicable in conjunction with some technologies for enhanced degradation of the waste such as **leachate recirculation, air injection** or **passive aeration**. The build-up of landfill gas under these types of cover systems is detrimental to their effectiveness.

Anaerobic bioreactor landfills [as well as **leachate recirculation systems**] have been successfully implemented in combination with **air injection**, creating an **aerobic landfill** condition (Reinhart, 2000). The use of these technologies in combination allows for rapid aerobic degradation near the air injection system, as well as reduced biogas generation, with enhanced anaerobic degradation occurring elsewhere. Air injection systems may be distributed throughout the waste mass during construction or installed near the surface of the waste mass at the end of construction.

5.3.6 Application in California

Air injection technology has been implemented for remediation of multiple sites in Europe to accelerate stabilization of the waste. This technology may be suitable for implementation in California. However, concerns about high temperatures and possible landfill fires plus the impact of moisture injection, often used to control high temperatures within the waste, on groundwater quality, may limit its applicability at unlined sites without geologic barriers beneath the waste.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study does not identify any landfill sites in California that have planned or implemented air injection technology.

5.3.7 Evaluation of Benefits and Barriers

The potential benefits of implementing air injection technology, in comparison with conventional MSW landfilling techniques, can be summarized as follows:

Environmental Protection

- reduced generation of methane due to aerobic degradation of waste;
- a potential for improved leachate quality due to a reduction of VOCs in operating or recently closed landfills;
- reduced landfill odor due to aerobic degradation of waste;
- improved performance of the final cover system and wider options for site-reuse due to accelerated stabilization of waste;
- decrease in long-term environmental risk due to accelerated stabilization of the waste mass;

Economic Effects

- increased air space in operating landfills due to enhanced degradation of waste;
- short duration treatment period (on the order of two years);
- system optimization may allow costs to be minimized;
- shortened post-closure maintenance and monitoring period; and

Other Issues

- requires no changes to Subtitle D landfill regulations;

The potential for barriers that may impact the successful implementation of air injection technology can be summarized as follows:

Environmental Protection

- insufficient moisture in the waste mass may result in high temperatures and landfill fires if moisture is not properly monitored and controlled;
- potential for increased leachate generation due to aerobic degradation and introduction of moisture to reduce temperatures may pose a problem for unlined landfills;

- improper monitoring and mixing of oxygen and methane may result in an explosive environment within the landfill;

Economic Effects

- requires an upfront capital cost expenditure to design and construct the system;
- requires high operational cost expenditure (energy costs for air injection) when compared to other landfill design and remediation technologies (i.e., anaerobic bioreactor);

Other Issues

- technology may not be applicable to all sites, based on site climate, cell size, site operations, moisture characteristics of waste, organic content of waste, and waste density; and
- potential for aesthetic issues due uncontrolled odor releases from landfill "blow-outs" (excessive air injection) and unsightly well installations through the landfill cover.

5.4 Leachate Recirculation

As described previously in Section 4.1, for the purposes of this study the term "leachate recirculation" is used to describe the process by which leachate (or other liquid by-product of waste disposal such as gas condensate) is injected into an existing landfill cell for the primary purpose of handling leachate generated at the site and does not necessarily suggest that the leachate is injected in a controlled manner to enhance microbial activity or that the containment system was specifically designed for the purpose of liquid injection. Any volume of leachate up to the field capacity of the waste may be recirculated without generating additional leachate or excess pore pressures, allowing this technology to be applied to sites in a wide range of climates with widely varying leachate generation rates.

The premise of leachate recirculation technology is that over time the environmental quality of recirculated leachate will improve as pollutants are flushed from the waste mass (Straub et al., 2001). To optimize this aspect of leachate recirculation, it has been suggested that leachate should be injected into the system at a rate nearing field capacity. This allows for optimized movement of liquid through the waste, as well as the enhanced extraction of pollutants from the waste mass. This lower rate of liquid injection produces a rate of degradation that is less than that of an anaerobic bioreactor, though the expected rate of degradation is still higher than in a conventional "dry" MSW landfill.

Leachate recirculation has been included in Section 5 of this report, Remediation of Existing Landfills, because this technology may be applied either to an existing landfill/landfill cell or to a specifically designed new landfill/landfill cell for the handling of leachate. This is in contrast to an "anaerobic bioreactor" system that, which is designed from the ground up for the optimization of degradation and is discussed in Section 4.1 of this report.

5.4.1 General Description

The primary components of a leachate recirculation system are essentially the same as the components of an anaerobic bioreactor and consist of the liquid injection system, the gas extraction system, and the emissions monitoring system. However, because the primary purpose of the system is the handling of leachate rather than the degradation of waste, the individual components may be designed differently than for an anaerobic bioreactor.

Liquid injection can be performed using a variety of methods including horizontal distribution trenches, vertical injection wells, trench fill and surface application. Depending on the volume of leachate recirculated, landfill gas generation is expected to be accelerated from that of a conventional MSW landfill. Therefore, it is likely that the gas collection system will be installed in conjunction with waste placement during the implementation of leachate recirculation. Although proper design of a leachate recirculation system should not result in an increased potential for uncontrolled emissions, the development of a detailed emissions monitoring system is recommended to verify performance of the landfill containment and control systems.

In addition to the design of the primary components listed above, consideration must be given to various characteristics and procedures that will vary from typical landfill characteristics and standard landfilling procedures as practiced in the U.S. In particular, consideration must be given to:

- waste characteristics;
- waste moisture content and the related effects on landfill stability;
- site climate conditions;
- compatibility of leachate collection and recovery system (LCRS) with injection rates; and
- daily cover characteristics.

5.4.2 Detailed Description and Process Options

5.4.2.1 Liquid Injection System

Various concepts for the injection of leachate into the waste mass have been developed and are described in Table 5-A:

Table 5-A: Leachate Recirculation Technology, Methods for Liquid Injection

Source: Warzinski, 2000

Method	Description
Vertical Injection Well	Designs vary with regard to the well diameter; the need for and the type of piping; the depth of the well; the well backfill material; and the injection rates. Vertical well injection can be designed and operated to be as labor intensive or as automated as desired. A more automated system will, obviously, result in greater up-front capital costs.
Horizontal Distribution Trench	A widely accepted method of recirculating leachate, horizontal distribution trenches also vary in design. They are generally employed to slowly introduce leachate into the waste mass. The system works very much like a leach field in a septic system. Designs vary with regard to the trench shape, the type of piping and perforation patterns, the slope of the pipe, and the infiltration rate. Again, the system can be as automated as desired, but automation increases up-front capital costs. This method is also a good alternative for recirculating leachate relative to environmental, health and safety, and aesthetic issues.
Trench Fill	This method consists of excavating a trench into the waste mass and pumping or transporting leachate into the open excavation, creating a pool. Within a short period of time, the leachate will dissipate into the waste mass. The trench can be recharged continuously with liquid to maintain a constant head of leachate in the trench. This is a cost-effective method, but can also raise environmental, health and safety, or other aesthetic- related issues.
Surface Application	This is the most cost-effective method, with leachate often applied directly to the working face during waste placement. This allows for the immediate wetting of waste prior to compaction. It also allows good distribution of liquids, thus minimizing channelization of liquids in the waste mass. The moisture provides lubrication during compaction of the waste and also reduces "rebound" or expansion of the waste upon completion of compaction. The addition of moisture prior to and during compaction typically results in a higher initial waste density. Methods for recirculating leachate at the working face include pumping the leachate from the landfill base LCRS or a leachate holding tank, to a temporary holding tank in a central area. A hose sprays leachate from the holding tank onto the waste, or a soaker hose upslope of the working face is used to allow leachate to seep into the open surface of waste. Another method consists of transporting leachate in a water truck to the working face for application. While application at the working face may be the most effective way to recirculate leachate, it can be the most operationally intensive method and raises potential safety and air emission concerns.

To evaluate injection rates, the capacity of the waste mass is calculated as well as the capacity of the LCRS. Based upon these two capacities, an injection rate is established that minimizes ponding, seeps and excessive head on the liner and allows adequate stability of the waste mass under the additional load of the injected leachate.

Increased rates of injection, nearing field capacity of the waste mass, as well as the development of preferential flow paths (as a result of waste heterogeneity and injection method) has the potential to result in unexpected and detrimental effects on the stability of the waste mass. High moisture content and preferential flow paths can cause increased pore pressures in the waste mass (either localized or global throughout the mass), resulting in a decreased factor of safety against slope failure. The potential for increased pore pressures within the waste mass under interim as well as long-term conditions should be carefully considered during design of the liquid injection system.

5.4.2.2 Gas Extraction System

The primary components of the gas extraction system in a leachate recirculation / liquid injection landfill are essentially the same as the typical gas extraction system installed at an MSW landfill during closure. The components generally consist of a horizontal gas collection layer installed at or near the top of the waste with vertical gas extraction wells at intervals across the landfill. If the leachate recirculation system is designed from the ground up, an alternative gas extraction system similar to the one described in Section 4.1.2.2 may be designed. This type of gas extraction system utilizes horizontal piping distributed through the waste mass at design intervals to accommodate the volume of landfill gas expected.

Depending on the characteristics of the waste mass, a sufficient volume of “green” energy in the form of methane is generally expected to be produced in this type of landfill to recommend its beneficial reuse. Therefore, during the design of the gas extraction system, options for reuse, including on-site reuse and sale to the local energy market, should be considered.

5.4.2.3 Emissions Monitoring System

The recirculation of leachate is expected to result in an increase of flow through the LCRS. Likewise, the potential for detrimental affects on soil and groundwater may be increased, even though the system should be designed such that no more leachate is generated than the LCRS can handle (e.g., less than 1 ft. of head on the liner system). Therefore, as in any landfill, a groundwater monitoring program to monitor the performance of the landfill containment system is an essential component of the landfill.

Although a properly design landfill gas extraction system for a landfill utilizing leachate recirculation technology should be as effective if not more effective than the system design for a traditional MSW landfill, the expected increase and acceleration in production of landfill gas results in an increased concern for uncontrolled emissions, especially prior to final closure. In addition, because gas extraction may be performed coincidentally with leachate injection, there is an increased potential for clogging of the gas extraction system. Therefore, as in all MSW landfills, a landfill gas monitoring program should be established during design to monitor the performance of the landfill gas extraction system.

5.4.2.4 Other Engineering Considerations

In addition to other site-specific considerations not discussed here, the following elements should be given special consideration during design of a leachate recirculation system.

Waste Characteristics

The design of a leachate recirculation system is highly dependant on the characteristics of the waste mass, especially the moisture content, hydraulic conductivity and field capacity under in-place compacted conditions. The site-specific waste mass should, therefore, be fully evaluated to determine the suitability of the waste source for application of a leachate recirculation system.

MSW is heterogeneous by nature, which inhibits the distribution of liquid through the waste mass and thus the participation of all portions of the waste mass in the pollutant flushing process (which is an important element of the leachate recirculation process). If MSW is not homogenized prior to landfilling, some of the waste may not participate in the flushing of pollutants from the waste, resulting in a reduced effectiveness with respect to the reduction in the potential for long-term detrimental environmental effects.

Homogenization of the MSW prior to landfilling allows wider distribution of leachate and minimizes the potential for the development of preferential flow paths. Homogenization can be accomplished by mechanical pretreatment, such as separation and shredding, which is discussed in detail in Section 3.1.

LCRS

A key component in the success of a leachate recirculation system is the ability of the LCRS to accommodate the volume of leachate generated. The LCRS must be continually operable. This is important for the development of the leachate recirculation system, which requires the introduction/re-introduction of liquids and may result in moisture conditions near field capacity in the waste mass above the LCRS. If the LCRS is not adequately designed for the volume of liquid entering the system, a saturated condition may develop at the base of the waste mass, violating the restriction of no more than one foot of head acting on the liner surface.

Experience in Canada, England, and in the U. S. demonstrate that the density and corresponding hydraulic conductivity of the waste itself prevents a continuous gradient from acting on the liner as long as the LCRS is continually operated. The design and construction of the leachate recirculation system must preclude short-circuiting of water to the LCRS from higher elevations in the landfill to ensure there is no continuous gradient acting on the surface of the liner (Jones, 2000).

In addition, the design of the LCRS should consider the increased leachate flow expected, especially in terms of the increased potential for physical and biological clogging. The compatibility of the LCRS and the chemical and biological make-up of site-specific leachate with respect to minimization of clogging potential is an important consideration during design of the leachate recirculation system.

Daily Cover

The use of traditional fine grained soil daily cover soil creates layers of lower permeability and is not considered beneficial in a leachate recirculation system for several reasons:

- it increases the potential for pore pressure generation in the waste between daily cover soil layers;
- it increases preferential flow through the waste mass; and
- it reduces the efficiency of gas extraction systems.

For these reasons, the use of temporary reusable daily cover, such as geomembranes, tarps, bio-degradable films or alternative permanent daily cover with higher permeability, such as tire shreds, has been recommended for leachate recirculation system. However, limited zones of low permeability daily cover soil can facilitate more uniform dispersion of leachate throughout the waste mass and in semi-arid and arid climates, the leachate generation rate may be low enough that controlled re-injection may not cause perched conditions to develop on top of the low permeability soil.

5.4.3 Global Application of Technology and Case Histories

Reports of successful application of leachate recirculation systems have been reviewed for sites across Europe, in South Africa and in the U.S., including sites in Wisconsin, Minnesota and Alabama. Reports of leachate recirculation have not, however, all been successful. The Bulbul

Drive landfill in South Africa and the Dona Juana landfill in Columbia, South America, both experienced massive failures due to poorly controlled (or uncontrolled) leachate recirculation. At Bulbul Drive, leachate perched upon a low permeability layer placed as interim cover at the interface between two phases of landfill development, generating excess pore pressures that led to instability (Brink, et al., 1999). At Dona Juana, the failure blocked passage of an adjacent river that provided local water supply. In this case, excessive volumes of leachate were recirculated under pressure into the landfill, causing an increase in pore pressure and an associated decrease in mobilized shear strength (Hendron, et al., 1999). Failure of the waste mass under intermediate fill conditions was also documented at a landfill in Ohio utilizing leachate recirculation (Wilson et. al, 2000). Although the volumes of leachate injection were monitored, two contributing factors were apparently not considered:

- the contribution of rainfall on the waste placement area, and
- the stability of the landfill under intermediate conditions.

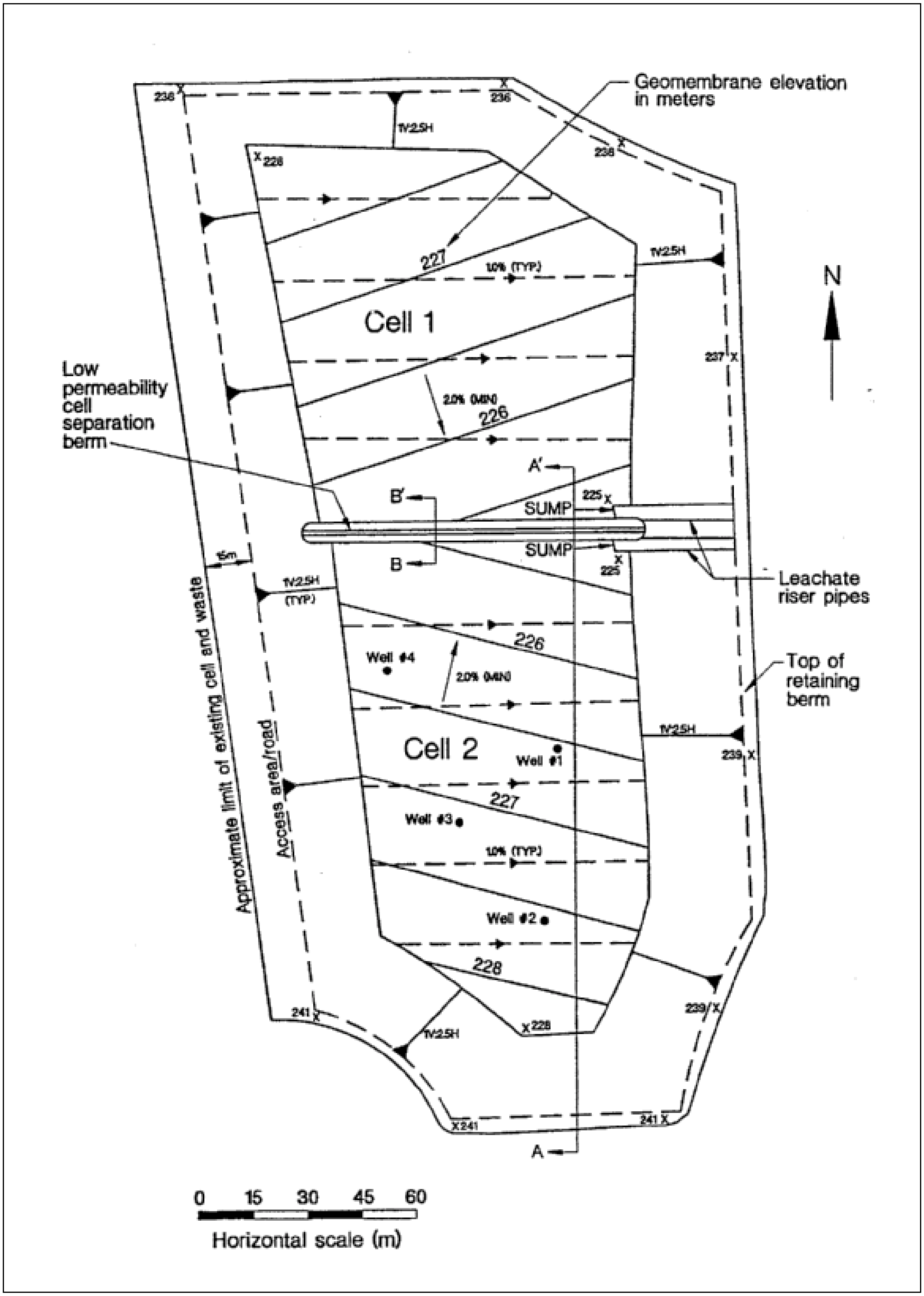
The following excerpts from Wilson et al., 2000, provide a description of the lateral expansion at the Ohio site, an account of the developments that results in failure and a summary of lessons learned from the case history.

The Geneva Landfill near Geneva, Ohio, received a permit for lateral expansion of the landfill in 1991. "Cell 2 of the lateral expansion was constructed first and began accepting waste in 1994. Cell 1, was constructed during the spring and summer of 1997. A composite liner system and a LCRS underlie both placement areas. On 3 October 1996 the landfill owner/operator received authorization to begin recirculating leachate back into the waste through vertical wells and a pipe network embedded in Cell 2. A slope failure occurred"…"in Cell 1 in August 1997. The failure caused extensive damage to the geomembrane in the [Cell 1] lateral expansion area." The site layout is depicted in Figure 5.5.

"The leachate recirculation system consists of 4 vertical wells connecting multiple hubs of horizontal trenches. The four vertical wells are located about every 30 m (100 feet) horizontally from the cell separation berm … throughout Cell 2. Each vertical recharge well has two hubs that connect to eight horizontal trenches that are filled with high permeability material, such as sand and/or tire chips. The trenches from the four vertical wells cover the majority of the cell floor to distribute the leachate. The lowest or deepest hubs are located approximately 9 m (30 ft) above the composite liner system."

"Discussions with landfill personnel indicate that leachate generation increased dramatically during and after rain events. This increase is thought to be the result of surface water infiltrating the recirculation system. Surface water run on in the recirculation area was increased by filling activities, the haul road, and the adjacent landfill slopes. This probably contributed to increased infiltration around the recharge wells. It will be recommended that facilities that use leachate recirculation actively promote surface runoff so large quantities of water do not infiltrate the waste and contribute to slope instability."

Figure 5.5: Geneva Landfill Lateral Expansion, Site Layout **Source: Wilson et al., 2000**



“Field observations suggest that the increase in leachate was influenced by surface water infiltrating in and around the vertical wells and flowing to the bottom of the wells. It is anticipated that liquids left the bottom of the vertical wells and flowed to the bottom of the waste, i.e. top of the geomembrane. The presence of the geomembrane and the 2% slope of the cell floor allowed the leachate to flow to and build up behind the low permeability cell separation berm. This was verified by a manhole located on the west side of Cell 2, furthest away from the sump. After a rain event, 0.9 to 1.5 m (three to five feet) of leachate usually would be present in the bottom of the manhole. It is anticipated that this buildup of leachate behind the cell separation berm resulted in the leachate outbreaks on the soil fill slopes in Cell 2. The slope failure occurred during or shortly after a large rainfall, which probably induced a large buildup of leachate behind the cell separation berm. Additionally, saturated conditions may have existed, and still may exist, at the bottom of the landfill due to the effectiveness of horizontal trench A (lower level) as compared to horizontal trench B (upper level) at diffusing fluids from the recirculation system.”

“The following lessons can be drawn from this case history:

(1) Excessive piezometric pressures may be generated by leachate recirculation leading to slope instability. A stability analysis should be conducted for this condition with the fluid pressures properly modeled. If a geomembrane is installed below the waste, the piezometric pressures only influence the materials and geosynthetic interfaces above the geomembrane. Therefore, piezometric pressures should not be applied to the interfaces below the geomembrane, e.g. the [compacted clay liner] CCL / geomembrane interface, in the stability analysis. However, the resulting earth and fluid pressures should be applied to the slope toe.

(2) Piezometric or seepage analyses should be conducted to assess the size and frequency of leachate outbreaks during normal and erratic leachate generation periods. Techniques for managing leachate outbreaks that do not adversely affect slope stability should be developed. Slopes at waste containment facilities should be regularly inspected for saturated areas and these areas should be treated accordingly.

(3) Failure to successfully manage surface water can result in saturated conditions and piezometric pressures that can cause slope instability. This may be especially relevant in the areas of leachate recirculation wells. Additional settlement may occur around these leachate recirculation wells due to increased waste degradation that may hinder surface runoff and increase infiltration. This unexpected increase in infiltration could adversely influence slope stability.

(4) The stability of interim or temporary waste slopes and stability during special circumstances arising from construction and operation activities, e.g. leachate recirculation, may represent the most critical condition that will occur at a waste containment facility and as such should be analyzed accordingly.

(5) State-of-practice limit equilibrium stability analyses and interface test results could have been used to predict this failure. As a result, it is recommended that state-of- practice testing and analyses and a suitable factor of safety be used when geosynthetics are involved."

5.4.4 Research Studies

Numerous studies have been performed or are ongoing to evaluate the performance and characteristics of landfill recirculation technology. In particular areas of research that have been studied to date include, but are not limited to:

- effects of leachate composition on quality improvement;
- observation of emissions;

- laboratory decomposition studies; and
- effects of waste processing on leachate quality improvement.

In addition, numerous lab-scale and field-scale studies are being performed to evaluate more closely the movement of liquid through the waste mass, the long-term improvement of leachate quality, and the effects of leachate recirculation on the environment.

Additional research on leachate recirculation has been recommended as follows (Rohrs, 2001; Bogner, 2001):

- evaluation of the time frame over which leachate contamination can occur given the improvements in leachate quality from leachate recirculation; and
- reduction in mobilized shear strength due to increased moisture content for application to slope stability analyses.

Because of the implications of a reduction in mobilized shear strength on the stability of the landfill, and the history of stability problems with leachate recirculation systems, it is recommended that a thorough evaluation of slope stability using increased pore pressure be performed prior to implementation of this technology.

5.4.5 Technologies in Combination

Due to the inherent heterogeneity of MSW, which can limit the effectiveness of **anaerobic bioreactor landfills** and **leachate recirculation systems**, it has been suggested that MSW be **mechanically pre-processed** prior to disposal in a bioreactor. This practice has not yet been implemented in the U.S., but results of studies in Europe (Binder, 2001) suggest that mechanical pre-processing of waste can provide positive results with respect to enhancing the rate of biodegradation in a bioreactor landfill and improving moisture distribution in a leachate recirculation system. Studies have shown that waste that has been bagged prior to disposal will not experience the same level of degradation as waste that has been removed from the plastic bags and shredded or milled.

Aerobic pre-treatment of waste prior to disposal in a **leachate recirculation system** allows for increase moisture content of the waste as well as accelerated improvement of leachate quality (Barton, 2000).

Anaerobic bioreactor landfills [as well as **leachate recirculation systems**] have been successfully implemented in combination with **air injection**, creating an **aerobic landfill** condition (Reinhart, 2000). The use of these technologies in combination allows for rapid aerobic degradation near the air injection system, as well as reduced biogas generation, with enhanced anaerobic degradation occurring elsewhere. Air injection systems may be distributed throughout the waste mass during construction or installed near the surface of the waste mass at the end of construction.

To achieve proper moisture conditions within the landfill, lower temperatures and enhance degradation, **leachate recirculation** may be used in conjunction with **passive aeration** for remediation of an existing landfill / landfill cell.

Use of **an exposed geomembrane cover system** or a **phytoremediation cover system** may not be applicable in conjunction with some technologies for enhanced degradation of the waste such as **leachate recirculation, air injection** or **passive aeration**. The build-up of landfill gas under these types of cover systems is detrimental to their effectiveness.

5.4.6 Application in California

Leachate recirculation is most beneficial with wastes with high organic content. Applicability must be evaluated on a site-specific basis given the composition of waste at the site, local climate conditions, and local site conditions. It should generally be applicable at all lined landfill sites to reduce leachate management costs and improve leachate quality. Because low permeability daily cover soil can inhibit the penetration of liquid and the distribution of moisture within the waste mass, alternative daily covers may be advisable at site where the daily cover soil is low permeability in nature. However, there do not appear to be any other barriers to leachate recirculation at lined landfill sites, and many lined sites within California recirculate leachate over lined areas for dust control.

Existing waste management regulations require the application of a final cover system within 180 days of the closure of the landfill. Unless leachate is reinjected under the final cover, the enforcement of this regulation may limit optimization of the leachate recirculation system for improving leachate quality.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study identifies six landfill sites in California that have planned or implemented leachate recirculation:

- Central Landfill
- Keller Canyon Landfill
- Vasco Road Landfill
- Acme Landfill
- Badlands Sanitary Landfill
- Potrero Hills Landfill

5.4.7 Evaluation of Benefits and Barriers

The potential benefits of implementing leachate recirculation technology, in comparison with conventional MSW landfilling techniques, can be summarized as follows (Burton, 2001; Warzinski, 2000):

Environmental Protection

- improved performance of the final cover system due to accelerated stabilization of waste;
- improved leachate quality with time in conjunction with stabilization of the waste mass; and
- decrease in long-term environmental risk due to accelerated stabilization of the waste mass.

Economic Effects

- reduced costs for leachate treatment and disposal;
- potential for increased revenue from the sale of landfill gas as an energy source, or reduced costs from the onsite use of landfill gas as an energy source;
- decreased cost due to use of alternative daily cover at soil-poor sites;
- increased air space due to enhanced degradation of waste and use of alternative daily covers;

The potential for barriers that may impact the successful implementation of leachate recirculation technology can be summarized as follows (Fourie, 2001):

Environmental Protection

- waste heterogeneity can cause preferential flow that limits the long-term beneficial effects on leachate quality with subsequent detrimental effects on the environment;
- increased potential for problems associated with internal and global stability if the landfill if not properly designed; and
- increased dependence on LCRS, liner system and gas collection system performance in the short-term to minimize emissions to the environment.

Economic Effects

- increased complexity of landfill systems and associated cost of design;
- increased up-front construction costs associated with the liquid injection and gas extraction systems;
- unquantified effect on operational costs to be evaluated on site-specific basis;

Other Issues

- technology may not be applicable to all sites, based on production of leachate, waste characteristics, capacity of existing LCRS and components of existing liner system;

5.5 Landfill Mining

"Landfill mining and [waste] reclamation are techniques whereby solid wastes which have previously been landfilled are excavated and processed. Processing typically involves a series of mechanical processing operations designed to recover one or all of the following: recyclable materials, a combustible fraction, soil, and landfill space. In addition, mining and reclamation can be used as a measure to remediate poorly designed or improperly operated landfills and to upgrade landfills that do not meet environmental and public health specifications (CalRecovery, 1993)." (Hudgins, 2001)

5.5.1 General Description

Landfill mining incorporates typical open mining techniques to excavate and process degraded MSW from landfill sites. This technology is primarily applicable to sites that are confronted with the following issues.

- The site has limited airspace, and there is no local alternate waste disposal site, such that landfill mining may be implemented to increase the airspace of the facility.
- The site has a limited soil source for cover material, such that landfill mining may be implemented to recover soil used for daily and/or intermediate cover.
- The site requires installation of a lining system or repair of an existing lining system to minimize future detrimental effects on the environment, such that landfill mining may be implemented to facilitate access to the liner.
- The site requires removal of waste from below the groundwater table, such that landfill mining may be implemented to access deep wastes.

Landfill mining utilizes standard construction equipment, including front-end loaders, backhoes and excavators to perform the mining operations. The material is excavated and removed to the on-site or off-site processing facility. The excavated material generally includes a mixture of MSW and/or other solid wastes with soil. The processing facility generally incorporates conveyor belts, screens, air separators, and magnets to sort the various waste streams from the fine-grained inert material (i.e., soil). The recovered materials (metal, paper, refuse derived fuel, etc.) are further processed, as necessary, prior to market distribution or re-use. The residual fine-grained material may be re-cycled as daily cover, and the remaining fraction of over-size un-recoverable material may be replaced in the landfill.

5.5.2 Detailed Description and Process Options

5.5.2.1 Mining Operations

During mining operations, mining personnel must wear appropriate personal protective equipment and must participate in an enhanced monitoring program to guard against the potential hazards that may be encountered during excavation. In addition, site monitoring for chemical and physical hazards should be incorporated into mining operations. Potential hazards are dependent on the historic waste stream at the site, but may include exposure to hazardous materials, methane and waste pathogens.

5.5.2.2 Material Processing and Recovery

On-site material processing and recovery may be performed in a temporary mobile facility that can be positioned close to the working face of the mining operations to minimize haul distance, or in a permanent facility, such as a mechanical pre-treatment facility for new incoming waste. The typical components of both types of facilities are the same. A description of a typical processing and recovery operation of mined material is provided in Hudgins, 2001, and is paraphrased here.

The excavated waste is placed on a conveyor belt system carrying the waste to a large screen, from which oversized, un-recoverable materials are removed. The fraction passing the large screen continues to a smaller screen. The fraction passing the smaller screen is classified as the soil fraction, which is comprised of organics and small ferrous materials as well as soil. The fraction retained on the small screen undergoes further processing, including air-separation to remove light components (i.e., paper) and magnetic separation to remove recoverable ferrous materials. The residual material after separation of these recoverable materials may be further processed through incineration or other pre-treatment method, or returned to the landfill.

The types of materials recovered and complexity of the recovery system should be evaluated on a site-specific basis. The demand for the recoverable materials should be considered, since many recycling facilities require a higher quality product than may be recovered from the landfill. Also, the composition of the historic waste stream should be evaluated to identify the expected quality and quantity of recoverable materials. Landfill mining technology is most applicable to highly degraded waste. There is little market demand for the recovery of “young” MSW and the more degraded the waste, the easier the recovery of recyclable materials.

5.5.3 Global Application of Technology and Case Histories

Sources discussing the global application and acceptance of landfill mining technology have not been identified. However, several sites in the U.S. and one in Israel are known to have implemented landfill mining technology for various reasons, as identified in Table 5-B.

Table 5-B: Sites Using Landfill Mining **Source: Hudgins, 2001**

Project	Objective	Notable Findings
City of Tel Aviv, Israel	Excavate the waste for the recovery of a soil amendment	First large-scale mining. In the Tel-Aviv LFMR project, the soil amendment had a total nitrogen, phosphorous and potassium (NPK) concentration of 1.4%.
Collier County, FL	Demonstration	The mined wastes were relatively well decomposed. The soil fraction accounted for about 60% of the infeed material. Ferrous and plastics fractions contained substantial levels of contamination.
Barre, MA	Part of a permit application to expand a private sanitary landfill	Excavation showed that some of the cells had been constructed to be almost completely impervious to the external penetration of water. The contents of these cells showed little decomposition. The recovered soil fraction was retained for use as cover material.
Bethlehem, NH	Landfill relocation process. The unlined landfill was mined.	Slight increases in conductivity; no changes in pH.
Edinburg, NY	One-acre demonstration to determine equipment needs, to develop optimal procedures for the excavation, separation handling and storage of dug materials and to determine the appropriate uses for the reclaimed material.	Results of analyses indicated that the soil fraction met the State of New York standards for compost and qualified for off-site use in a variety of applications, including clean fill in public construction projects and daily landfill cover.
Lancaster, PA	Wastes were excavated from an 18-acre cell and added to fresh MSW as supplementary fuel.	The energy value of the mined material is estimated to be US $33/tonne. Material recovery was less attractive economically and, therefore, was not a component of the operation.

In addition, landfill mining and resource recovery has been implemented in conjunction with aerobic or anaerobic bioreactor technology at least one site identified in the United States: Live Oak Landfill near Atlanta, Georgia. However, due to the low quality of the compost recovered from the landfill mining and recovery process and the high relative cost of implementing both technologies, it is our understanding that the project has been suspended.

5.5.4 Research Studies

Very little existing or ongoing research on the applicability and effects of landfill mining has been identified during this study. Hudgins, 2001, was the sole source for the development of this discussion, and was based primarily on experiences at a few sites. To fully evaluate hazards and operational considerations, further evaluation of experiences at existing sites is recommended if this technology is to be considered for application.

5.5.5 Technologies in Combination

A model for applying **landfill mining** technology in conjunction with an **aerobic landfill** has been proposed by Hudgins, 2001. This model consists of a four-cell "sustainable" landfill scheme, filled sequentially with each cell in a different phase of development, as shown in Figure 4.2 (p. 47). This model allows for degradation of the MSW prior to mining and recovery of recyclable materials. The residual material may then be reused in the landfill as daily cover material.

Use of **exposed geomembrane cover systems** as sites where **landfill mining** is planned can reduce costs and simplify operations.

5.5.6 Application in California

In general landfill mining technology is primarily applicable to sites that are confronted with the following issues.

- The site has limited airspace, and there is no local alternate waste disposal site, such that landfill mining may be implemented to increase the airspace of the facility.
- The site requires installation of a lining system or repair of an existing lining system to minimize future detrimental effects on the environment, such that landfill mining may be implemented to facilitate access to the liner.
- The existing waste unit is adversely affecting the environment (e.g., groundwater quality) and must be removed or otherwise remediated.

The application of landfill mining technology in California may be limited by the following factors.

- The waste disposed in California's landfills may not yet be sufficiently degraded to optimize the recovery for recyclable materials.
- The market demand for recyclable materials recovered from degraded MSW may not be sufficient to economically justify implementation.

However, in high-density areas where land for disposal is scarce, landfill mining technology may be found to be a cost effective, logistically feasible, and environmentally conscious alternative. Furthermore, in cases where an existing landfill is adversely impacting the environment, landfill mining may be economically superior to other remediation options.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study identifies one landfill site in California that has planned or implemented landfill mining:

- City of Clovis Landfill.

5.5.7 Evaluation of Benefits and Barriers

The potential benefits of implementing landfill mining technology can be summarized as follows (Hudgins, 2001):

Environmental Protection

- reclaims used airspace, allowing reuse of landfill cells;
- allows for installation or repair of liner system;
- allows for recovery and recycling of materials;
- reduces / eliminates environmental impact of unlined cell;

Economic Effects

- reclaims used airspace, lowering costs associated with landfill expansion;
- potential for increased revenue due to sale of recovered materials;
- allow for reuse of residual fine-grained material as daily cover, reducing earthwork costs;
- provides a potential for reduced post-closure costs;
- flexibility in complexity of processing system allows for control of costs vs. effectiveness; and

Other Issues

- landfilling of residual waste requires no changes to Subtitle D landfill regulations.

The potential for barriers that may impact the successful implementation of landfill mining technology can be summarized as follows:

Environmental Protection

- increased hazards to mining personnel;
- increased odors and other emission issues;

Economic Effects

- potential for cost of excavation to outweigh the benefits of implementing the process;
- material processing requires an upfront capital cost expenditure to design and construct the facility;
- low quality of recovered materials may reduce marketability, and thus reduce cost recovery;

Other Issues

- increased operational monitoring requirements;
- applicability dependent on the degradation of the landfilled waste (most applicable to degraded waste); and
- applicability dependent on the market demand for recycled materials and the characteristics of the incoming waste stream.

6 Industry Standards, Certifications and Guidance Documents

6.1 Standards and Certifications

To keep pace with emerging technologies in landfill operations and design, various standards and certification programs have been developed. To our knowledge, these standards and certifications programs are entirely voluntary in the United States: we are not aware of any regulatory requirements for certification or compliance with industry standards. These industry-developed standards allow the waste management industry to regulate itself and advance its standards of practice. By developing standards and certification programs, the industry has in effect developed a set of industry "best practices" which it strives to implement.

Standards have been defined to provide recommendations for equipment, processes, environmental safety, and personnel requirements. Certification programs have been developed to train industry personnel in these industry standards and to provide information on new technologies. This study focuses on standards and programs developed by three organizations:

- American National Standards Institute (ANSI);
- International Standards Organization (ISO); and
- Solid Waste Association of North America (SWANA).

A description of existing standards and certification programs and requirements follows.

6.1.1 ANSI Standards

Working through ANSI, the Environmental Industry Association (EIA) has developed standards for equipment technology and operations in the areas of wastes and recyclable materials. These standards were developed by industry veterans through the ANSI consensus process for development of standards and are defined under the ANSI designation Z245 (Fickes, 2002). The applicable standards are summarized in Table 6-A.

Table 6-A: ANSI Standards Applicable to Landfill Management **Source: Fickes, 2002**

Standard	Summary
ANSI Z245.1-1999	Covers technology for collection, transportation and compaction equipment for wastes and recyclable materials. Establishes safety and design requirements for the manufacture, reconstruction, modification, maintenance, service, operation and installation of mobile collecting, transporting and compacting equipment. Applies to everyone engaged in the manufacture, modification, operation, cleaning, maintenance, service or repair of this equipment.
ANSI Z245.2-1997	Relates to equipment technology and operations for stationary compactors. Includes safety requirements for the manufacture, reconstruction, modification, maintenance, service, operation and installation of this equipment.
ANSI Z245.30-1999	Sets standards for waste containers. Focuses on safety requirements for the manufacture, reconstruction, use, modification, maintenance, service, operation and installation of containers, two-wheeled carts and two-wheeled container lifters.
ANSI Z245.41-1997	Focuses on recycling facilities. Establishes safety requirements for people who design, manufacture, assemble, modify, operate, clean, maintain, service and repair materials recovery facilities (MRFs) processing commingled recyclable materials.
ANSI Z245.5-1997	Specifies safety requirements for baling equipment ranging from the manufacture through the operation of mechanical, electro- mechanical, hydraulic, and electro-hydraulic balers used in recycling, solid waste disposal, and raw materials handling.
ANSI Z245.60-1999	Focuses on waste container dimensions. Facilitates the dimensional compatibility between various types of containers and equipment designed to lift and dump these containers. Promotes the identification of compatible containers and lifting equipment by firms that manufacture, reconstruct, use, modify, maintain, service, operate and install containers.

6.1.2 ISO Certification

In an effort to provide international standardization of environmental management practices, ISO has developed the ISO 14001 standards for environmental management systems (EMS). As it is defined here, an EMS is the component of an industrial framework that defines the organizational structure and respective responsibilities, planning activities, practices and procedures, and resources for developing, implementing, achieving, reviewing and maintaining the adopted environmental policy (Belgiorno et al., 2001).

The ISO 14001 standard is intended to be applicable to a variety of organizations and industries. The voluntary international standard specifies requirements for the following elements of an EMS:

- establishing environmental policy;
- identifying and evaluating environmental aspects and impacts of products, activities, and services;

- defining an environmental program though specification of environmental objectives and quantitative targets;
- implementing and operating EMS programs to meet objectives and targets;
- auditing and corrective action; and
- management review.

As it applies to landfill operation, implementation of the ISO 14001 EMS standard may be beneficial for several reasons. The process provides an opportunity to reduce waste and emissions, through a review of operating practices and focus on opportunities for ongoing performance improvements. Having an effective EMS in place makes it easier to identify and implement changes to technological systems required by revisions to environmental regulations. Improved environmental management systems may serve to lower long-term costs and increase efficiency.

While some European Community countries may require ISO compliance, compliance with ISO standards in the United States is entirely voluntary. However, in some industries some large corporations may insist on ISO certification or give preference to suppliers who are ISO-certified. Furthermore, international recognition of the ISO standards may serve to enhance corporate reputation (Reyneri et al., 1999).

6.1.3 SWANA Certification

The Solid Waste Association of North America (SWANA) currently sponsors certification programs in six disciplines, including:

- <u>collection systems</u>: assists collection manager, sanitation superintendents, hauling managers and others in designing and implementing efficient and effective collection systems;
- <u>construction and demolition</u>: provides C&D personnel information about the disposal and reuse of C&D materials and addresses the planning, design and management of C&D landfills.;
- <u>landfill management</u>: provides landfill managers, inspectors and others involved in sanitary landfills information about the planning, design and management of MSW landfills;
- <u>municipal solid waste management</u>: addresses the principles and practices of managing an integrated MSW management system;
- <u>recycling systems</u>: provides recycling managers and others information about the planning, design and management of waste reduction, recycling and composting systems; and
- <u>transfer systems</u>: addresses the increased interest in transfer stations and provides transfer station managers and others the opportunity to learn more about transfer station design and operation.

Three levels of certification are available, depending on the experience and eligibility of the personnel (manager, technical associate, or inspector [landfill certification only]).

6.2 Guidance Documents

Existing regulations provide characteristic and performance criteria for landfill systems, yet, with a few isolated exceptions, they do not provide guidance on how to achieve the minimum requirements for those criteria. Some U.S. states have taken it upon themselves to develop guidance documents, providing recommendations for landfill design methods and similar topics. The purpose of these guidance documents is two-fold:

- they allow more consistency between landfill designs by providing consistent methodology; and
- they assist regulators in evaluating the quality of a design submitted for review.

These documents are relatively inexpensive for the agencies to produce and have the potential to provide substantial benefit if their use is recommended by regulators. For example, the Ohio EPA has developed dozens of engineering guidance documents, including a policy entitled "Geotechnical and Stability Analyses for Ohio Waste Containment Facilities" (Ohio EPA, 2002). This document provides guidance for demonstrating that stability requirements for waste containment facilities regulated by the Ohio EPA. The document provides recommendations for the following components of geotechnical and stability analyses:

- subsurface investigation;
- materials testing;
- liquefaction potential evaluation and analysis;
- bearing capacity and settlement analyses;
- hydrostatic uplift analyses;
- deep-seated failure analysis;
- shallow failure analysis;
- geosynthetic anchorage analysis; and
- reporting.

The document was developed with the intent that use of its methods and procedures would satisfy stability requirements mandated by the Ohio EPA. However, site-specific conditions may affect the applicability of some of the methods and procedures, such that sampling, testing and analyses should be tailor fit to each individual site.

6.3 Application in California

The standards and certifications described in this study are generally applicable in California on a voluntary basis. At the present time, no compelling reason has been identified to suggest that these voluntary, industry-developed standards and certification programs should be changes into mandatory regulatory programs. There is no evidence that environmental protection at landfills has been compromised by lack of training or failure to adhere to standards. In this sense, the industry does an adequate job in regulating itself and there seems no reason to add another layer of regulatory scrutiny on top of these programs, as it would provide little benefit at a substantial cost (to develop and administer such programs). However, adherence to industry standards and self-certification can simplify regulatory oversight, and hence these programs have substantial value. Methods to provide incentives for owners to voluntarily adopt these programs may be one way to encourage further implementation of these programs. For example, CIWMB could sponsor a 5% reduction in CIWMB tipping fees for landfills (1) which develop and implement ISO 14001 certifications programs and (2) at which all operators have completed SWANA MOLO (Manager of Landfill Operations) courses.

Regulatory agencies in the State of California have yet to develop guidance documents for the design of MSW landfills. As was discussed in Section 6.2, guidance documents can be beneficial in that they provide owner with a framework for design and assist regulators in ensuring quality through consistency in design methods. While there is a one-time cost to the state for developing these documents, they should not increase costs to operators because the methods and processes defined in the documents are things the designers should already be doing. They may, in fact, reduce design costs by reducing uncertainty with respect to what is expected in a design submittal. They mitigate the potential for design oversights and provide substantial guidance to regulators reviewing designs. However, care must be taken so that the guidance document is not too prescriptive, rigid or inflexible. It should not specify what design methods must be used but should provide examples of acceptable design approaches while being open to implementation of alternative design methods and new design methods, if properly documented, and to recent developments concerning particular engineering issues.

7 Summary of Technologies

This section provides a brief summary of all the information provided in Sections 3 though 6 of this report as Table 7-A, near the end of this Section. This table provides a general description of each of the technologies included in this study and summarizes process options, global applications to date, benefits, barriers, ongoing research and research needs, and costs of each technology.

Because of the significance of the applicability of each of the technologies in California to the results of this study, this topic is discussed separately in the remainder of this Section and is presented in Table 7-B, at the end of this Section. Additional details regarding the applicability of individual technologies in California are presented in their respective sections, Sections 3 through 6 of this report.

7.1 Mechanical Pre-Processing

Waste separation has been implemented in many communities in California in the form of material recycling facilities (MRFs). These facilities are used primarily for separation of recyclable materials prior to disposal and generally do not incorporate additional mechanical pre-processing steps such as size-reduction (shredding, crushing).

Size-reduction (i.e., waste shredding) has been found to both increase capacity due to increased initial disposal density and accelerate the degradation of waste after disposal, increasing the potential for enhanced revenue from landfill gas to energy projects. It has not been incorporated into MRFs primarily due to the added cost and the lack of a perceived benefit. If the MRF is not owned by the same company that operates the landfill, the additional cost of shredding does not provide any additional benefit to the MRF owner because landfill tipping fees are typically based on weight. Therefore, the current structure of the waste industry may limit the economic feasibility of incorporating size-reduction at MRFs, unless the shredding facility is owned by the landfill company.

Baling of waste is planned or being used at several California landfills. Baling allows for increased compaction of waste prior to landfilling, reducing demand for air space. The bales can be stacked higher and at a steeper angle. Landfilling baled waste allows for a cleaner operation, by reducing the need for daily cover. However, placement of baled wastes in landfills may adversely affect the time required for environmental stability of the landfill as it prolongs degradation of wastes.

Current regulations place no barriers to implementation of mechanical pre-processing.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study identifies the following landfills as having planned or implemented some form of mechanical pre-processing:

- Fort Irwin Sanitary Landfill;
- Edwards AFB Main Base Sanitary Landfill;
- West Miramar Landfill;
- Potrero Hills Landfill; and
- West Contra Costa Sanitary Landfill.

However, it is likely that some form of mechanical pre-processing is performed at other landfills in California.

7.2 Biological Pre-Treatment

Anaerobic and aerobic pre-treatment provide substantial benefits, including enhanced disposal capacity due to reduced disposal volumes, accelerated waste stabilization, accelerated post-closure development, and the recovery and reuse of “green” energy (i.e., methane) when applied to wastes with a high organic content. However, due to the high initial capital costs associated with this technology, most U.S. landfill operators seem to consider the lower capital cost option of in-place biological treatment (i.e., bioreactors) as a more promising technology, even in arid and semi-arid climates where the applicability of anaerobic bioreactor technology may be limited by limited availability of sufficient water.

No technical or regulatory limitations precluding the application of these technologies in California have been identified for either of these technologies. A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study identifies the following landfills as having planned or implemented some form of biological pre-treatment:

- West Miramar Landfill;
- Potrero Hills Landfill; and
- West Contra Costa Sanitary Landfill.

However, it is likely that some form of biological pre-treatment is performed at other landfills in California.

7.3 Thermal Pre-Treatment

Thermal pre-treatment in the form of incineration has been implemented at several sites in California. Incineration reduces the amount of waste to be landfilled. However the widespread application of this technology is dependent on several factors including the composition of the waste stream, local air quality regulations, and the potential for detrimental effects on the environment from the disposal of incinerator bottom ash. Furthermore, California’s metropolitan areas have been designated “air quality non-attainment zones” by the USEPA, and implementation of thermal pre-treatment technologies in these areas may be restricted or may require “air pollution credits”.

If pyrolysis is implemented instead of incineration, the potential for detrimental effects on the environment may be reduced and air quality regulations may be met. However, no integrated system of pyrolysis and large-scale material recovery of MSW has been identified.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study does not identify any landfill sites in California are performing thermal pre-treatment. However, several off-landfill thermal pre-treatment facilities were identified in Section 3.3.3.

7.4 Anaerobic Bioreactors

Anaerobic technology is most advantageous with wastes with high organic content and requires relatively large quantities of liquid (generally water). The anaerobic bioreactor method can enhance the degradation of waste prior to closure of the landfill, increasing air space, the recovery and reuse of “green” energy (i.e., methane), and reducing degradation potential of the material following closure, thereby reducing the long-term effects on the environment. Due to the need for an ample liquid supply source, typically in the form of water or leachate, this technology may not be applicable in arid environments. In semi-arid conditions, a feasible alternative may be the construction of a single anaerobic bioreactor cell which is operated in tandem with traditional landfill cells, using leachate from all cells combined with surface water runoff as the liquid for injection in the bioreactor cell.

Various regulatory constraints may limit the applicability of anaerobic bioreactors. Current regulations do not allow the construction of an anaerobic bioreactor cell with any base containment system other than the Subtitle D prescriptive liner system, which may result in additional cost for the construction of a compacted clay liner on the cell sideslopes. Current federal regulations further restrict recirculation to leachate that originates within the landfill, though a recent interpretation of an existing rule expanded this to include water from non-contaminated sources (Reinhart, 2000). In addition, existing waste management regulations require the application of a final cover system within 180 days of the closure of the landfill. Depending on the details of the individual bioreactor design, the enforcement of this regulation may limit optimization of the bioreactor system unless leachate and "make-up" water may continue to be injected beneath the final cover.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study identifies the following landfills as having planned or implemented anaerobic bioreactors:

- San Onofre Landfill (proposed);
- Yolo County Central Landfill; and
- Las Pulgas Landfill (proposed).

7.5 Aerobic/Semi-Aerobic Landfill

The governing principle of aerobic / semi-aerobic landfill technology is that the introduction of air into the landfill induces aerobic degradation of the waste. The degradation of waste occurs more quickly than under anaerobic conditions and produces carbon dioxide gas rather than methane. The waste type, climate and in-situ moisture content are key components to the applicability of aerobic or semi-aerobic landfill technology to a landfill site, because of the risk for landfill fires associated with the introduction of oxygen.

Semi-aerobic landfill technology utilizing passive aeration has been implemented in Japan and other Asian countries, primarily in areas where heavy rains increase the moisture content of the waste. This technology has not yet been tried in North America or Europe. It may have applicability to areas in northern California where climate conditions are somewhat similar to parts of Japan. However, semi-aerobic landfill technology has not yet gained widespread acceptance in the U.S. Aerobic landfills have been implemented at several locations in the U.S., though none have been identified in California.

One barrier to implementation of this technology may be the tendency of some regulators to consider the high temperatures that accompany aerobic decomposition (sometimes on the order of 160 to 180 F) to be indicative of a landfill fire.

7.6 Alternative Base Containment Systems

Experience with the field performance of single composite liner systems (USEPA, 2002a) indicates that liner leakage rates will be very small for MSW landfills with a single-composite liner system properly designed and constructed to minimum state and federal criteria with good CQA practices. Therefore, enhancements to the prescriptive single composite liner system (e.g., double liners, white liners, etc.) should only be necessary for MSW landfill sites in California with exceptional conditions (i.e., karst geological features, sites over sole source aquifers without geological barriers beneath the waste unit, or sites where groundwater cannot be monitored). Electrically-conduction geomembranes are probably the most cost-effective means of enhancing the reliability of the prescriptive single composite liner system.

Encapsulation of the geosynthetic clay liner (GCL) can significantly increase the shear strength of the GCL, and may be particularly applicable to canyon landfills, where use of a GCL is necessary because the construction of a low permeability soil liner is either cost-prohibitive or technically infeasible. Encapsulated GCLs have already been used at over a half-dozen landfills in California.

For sites with high groundwater, one alternative base containment system that may be applicable is the inward gradient landfill. The premise behind an inward gradient landfill is that by constructing the landfill cell below the surrounding groundwater table and providing a higher conductivity flow path, groundwater is directed inward toward the waste, protecting the surrounding environment from leachate contamination. However, implementation of an inward gradient landfill without construction of a base liner system, as has been implemented at sites in Canada, is precluded by state and federal regulations that require a 5 ft separation between groundwater and waste. Notwithstanding, when constructed in conjunction with the liner configurations described in Section 4.3.1.6, inward gradient landfill technology may be applicable to sites in California with high groundwater conditions.

The cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study identifies the following landfills where alternative base containment system have been planned or implemented:

- Azusa Land Reclamation Company Landfill (double liner system);
- CWMI Kettleman Hills Facility (double liner system);
- Rock Creek Solid Waste Facility (double liner system); and
- Woodville Disposal Site (white geomembrane).

7.7 Alternative Cover Systems

In general, non-barrier cover systems (i.e., monolithic evapotranspirative cover systems, capillary break cover systems, and phytoremediation cover systems) have been developed with arid and semi-arid climates in mind, as are found in most parts of California. However, regulatory limitations (such as conditional long-term approvals) may dissuade owners from employing them. Studies are ongoing to evaluate the performance of these types of alternative cover systems in arid and semi-arid climates. These studies generally employ conditional approvals, wherein the owner is prohibited from withdrawing money from financial assurance funds until after several years of post-construction monitoring has been completed. While regulations that allow for engineered alternatives to the prescriptive cover system facilitate the application of alternative cover systems in California, long-term conditional approvals may dissuade some owners from employing alternative covers even in cases where it is recognized that the prescriptive cover (i.e., a clay barrier cover) will not perform satisfactorily.

7.7.1 Monolithic Evapotranspirative Soil Cover System

The monolithic evapotranspirative (ET) soil cover is the most common alternative cover system installed in arid and semi-arid regions of the western United States. Over a dozen ET covers have been granted conditional approval in southern California. An ET cover relies on the storage capacity, evaporation and transpiration characteristics of the cover soil. Infiltrating surface water is stored in the cover soil during the wet periods and released to the atmosphere through evaporation and transpiration during the dry season.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study identifies 22 landfills where monolithic soil covers have been proposed or implemented. However, the cross-media inventory does not specify whether these covers have been designed as monolithic evapotranspiration soil covers and thus are not listed here. California landfills where evapotranspiration cover systems are known to have been planned or installed are included in Table 4-D.

7.7.2 Capillary Break Cover System

A capillary break cover system is an evapotranspirative cover system that uses a layering sequence that inhibits infiltration by fully utilizing capillary suction within the cover soils. A capillary break cover system is similar to a monolithic ET cover in that it is dependent upon the evaporation and transpiration characteristics of the cover soil to minimize infiltration. However, proper design of a capillary break cover system allows the storage capacity of the cover soil to be maximized. In addition, the capillary break cover facilitates the collection of landfill gas from the capillary break layer (which the ET cover does not include).

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study does not identify any landfill sites in California have planned or installed capillary break final cover systems.

7.7.3 Phytoremediation Cover System

Similar to an ET cover system, a phytoremediation cover system uses a monolithic soil cover and relies on the storage capacity, evaporation and transpiration characteristics of the cover soil to minimize percolation into the waste mass. However, unlike an ET cover system, a phytoremediation cover system is designed to incorporate a variety of vegetative types, from grasses to trees, which minimize infiltration and enhance degradation of the waste mass. A phytoremediation cover may actually rely upon intrusion of the root system into the waste or contaminated soil to facilitate degradation.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study does not identify any landfill sites in California that have planned or implemented phytoremediation final cover systems.

7.7.4 Exposed Geomembrane Cover System

An exposed geomembrane cover system (EGCS) generally consists of a geomembrane overlying a foundation soil layer, as shown in Figure 4.12, without drainage, topsoil or vegetation layers that may be included in a typical cover system. An EGCS may be considered as a viable alternative to a typical cover system in certain special situations where aesthetics are not a significant issue, infiltration control is critical, or stability concerns preclude placement of a vegetative cover soil layer.

In general, exposed geomembrane cover systems are applicable to sites in California, for limited term applications (up to 10 to 20 years). However, sites with high winds or aesthetic requirements may not be suitable for application of this technology. There are no barriers in the current regulations to the application of this technology.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study identifies one landfill in California where an exposed geomembrane cover system is proposed:

- Azusa Land Reclamation Company Landfill.

7.7.5 Delayed Closure

As suggested by the USEPA (1991), it may be appropriate to propose the installation of an intermediate cover instead of a final cover for two to five years following the end of waste placement to allow anticipated settlement of the waste mass occur. This concept is not new, but it has not yet been widely implemented. Sites continue to be closed soon after waste placement. This practice reduces the generation of leachate and may allow the site to be redeveloped quickly, but dramatically slows the degradation process. By allowing a delay in closure, the waste continues to degrade, reducing the potential for long-term impacts on the environment.

Delayed closure is generally applicable to sites throughout California, depending on the characteristics of the waste, the local climate, and the type of base containment system. Delayed closure may not be applicable in areas where urban development has encroached upon a site, as such sites are generally pressured to close shortly after waste acceptance is ceased in order to mitigate nuisance concerns such as odors and vectors.

No sites have been identified where delayed closure has been approved by a regulatory agency to allow enhanced degradation of the waste mass prior to closure. One site, Millikin Landfill in California, is reportedly nearing the end of a four to five year delayed closure, though the purpose of this delay has not been identified and regulatory approval of the delay has not been verified.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study does not identify any landfill sites in California that have planned or implemented a delayed closure strategy.

7.8 Landfill Gas Applications

7.8.1 LFG Destruction

The basic technology for the destruction of LFG, with variations, is well established and has not changed much during the past ten years. However, two recent innovations are high-temperature flares and flameless noncatalytic oxication, which almost completely oxidize the methane in LFG. Because these new technologies have not been implemented in the U.S., it is unknown whether performance and emissions standards will meet U.S. and California criteria. Compliance should be demonstrated prior to full-scale implementation at sites in California.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study does not identify any landfill sites in California that have planned or implemented high temperature flares or flameless noncatalytic oxidation of landfill gas.

7.8.2 LFG Conversion to Electricity

All of the technologies for the conversion of landfill gas to electricity discussed in this study (IC engines, combined cycle plants, microturbines and fuel cells), with the exception of Stirling cycle engines, have been deployed in California. The quantity of LFG generated is a critical factor in determining the viability of any of these technologies, and the impact of the arid climate in some portions of California on LFG generation may limit their applicability.

Air quality concerns, particularly in severe non-attainment areas, can impact the application of landfill gas conversion technologies. IC engines currently produce the highest emissions, although current initiatives to produce cleaner burning engines may improve this dramatically. Microturbines, combined cycle plants, Stirling engines and fuel cells, with their much lower emissions than other electricity generation technologies, may be more desirable in areas with significant air quality concerns.

Other state regulations, such as those aimed at the utilization of renewable energy resources, may have a positive impact on the application of landfill gas conversion technologies.

Several California state regulations currently affect the LFG industry. Among them is the Renewables Portfolio Standard instituted by the Governor of California on 12 September 2002, which requires utilities to purchase at least 20 percent of their electricity from renewable resources (includes LFG) by the year 2017. This law was enacted on 1 January 2003 and requires an increase of 1 percent per year until the year 2017.

Consumer surveys show that most people will pay an additional 10 percent to utilize renewable energy sources (Arner, 2002). Therefore, if green energy in the form of LFG to energy programs is made available to California, it is anticipated that many consumers may be willing to pay a small premium to receive it. However, compared to the cost of developing a LFG to energy (LFGTE) technology, this will not offset a significant amount of development cost.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study identifies several landfill sites in California that have planned or implemented landfill gas-to-electricity facilities (or are selling landfill gas for offsite conversion). These facilities include:

- Acme Landfill;
- Altamont Landfill and Resource Recovery Facility;
- Bailard Landfill;
- Central Landfill;
- City of Palo Alto Landfill
- City of Santa Cruz Sanitary Landfill;
- Coastal / Santa Clara Landfill (Pre-1993);
- Crazy Horse Sanitary Landfill;
- Mission Canyon (Pre-1993);
- Monterey Regional Waste Management District / Monterey Peninsula Landfill;
- Olinda Alpha Sanitary Landfill;
- Otay Landfill;
- Puente Hills Landfill;
- San Marcos Landfill;
- Scholl Canyon Sanitary Landfill;
- Sycamore Sanitary Landfill;
- Tajiguas Sanitary Landfill;
- West Contra Costa Sanitary Landfill;

- West Miramar Landfill, and,
- Yolo County Central Landfill.

7.8.3 LFG Use as Medium Btu Fuel

One of the simplest and most direct ways to use LFG is through direct use as a medium Btu fuel. Common medium Btu fuel uses include industrial boiler fuel, wastewater treatment plant sludge incinerators, and steam space heat. A recent innovative use is to provide heat for greenhouses. Utilization of LFG as a medium Btu fuel should not face significant implementation hurdles in California from either a regulatory or economic standpoint.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study identifies four landfill sites in California that have planned or implemented landfill gas medium Btu projects:

- Bradley Landfill West and West Extension;
- Cold Canyon Landfill Solid Waste Disposal Site;
- Lopez Canyon Sanitary Landfill; and
- University of California Davis Sanitary Landfill.

7.8.4 LFG Conversion to High Btu Fuel

Several technologies exist to purify LFG to pipeline quality gas, which can then be sold to an industrial or commercial user of fuel trucks, buses and other vehicles, or distributed into a natural gas pipeline. Additional costs to remove cancer-causing chemicals from natural gas (i.e., CNG or LNG) intended for off-site distribution, may limit the utilization of LFG as a high Btu fuel to on-site industrial applications or vehicle fuel. One of the obstacles to widespread utilization of LNG as a vehicle fuel is the lower Btu value of LNG compared to diesel fuel. For applications such as refuse trucks, this problem may be overcome by installing the LFG-to-LNG conversion plant and fueling station at the landfill itself. Requirements for fleet vehicles (such as those used by the SCAQMD) to have low emissions, may improve the economic viability of LFG-to-LNG projects. The expected increase in demand for natural gas (i.e., CNG) in the future, would make the use of LFG as a high Btu fuel a more viable option.

Waste Management, Inc. (WMI) is currently working with CryoFuel Systems to construct and operate two pilot LFG-to-LNG conversion plants at landfills in northern California. WMI expects the plants to be operational during the first quarter of 2004 (Waste Management, 2003).

The Sanitation Districts of Los Angeles County operates a plant that converts LFG from the Puente Hills landfill to CNG using membrane technology. The plant has a capacity to produce 1,000 gallons per day, but currently produces about 100 gallons per day that is used to fuel a fleet of 13 vehicles (vans and tractors). In 1992 dollars, the capital cost of this project was $1,100,000 (Wheless et. al., 1996).

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study identifies three landfill sites in California that have planned or implemented landfill gas high Btu projects:

- Chicago Grade Landfill;
- Puente Hills Landfill; and

- South Chollas Landfill (Pre-1993).

7.8.5 LFG Use in Leachate Evaporation

Direct flare injection technology for leachate evaporation is not universally accepted and could be a permitting challenge in southern California due to non-attainment area conditions. Permitting might be difficult because combustion is not complete, and some volatiles (e.g. vinyl chloride) and metals may be present in emissions.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study does not identify any landfill sites in California that have planned or used LFG for the evaporation of leachate.

7.8.6 LFG Conversion to Industrial Products

Given the low emissions of technologies for the conversion of LFG to industrial products, especially of green house gases, these technologies should not face significant application hurdles in California.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study does not identify any landfill sites in California that have planned or implemented the conversion of LFG to industrial products.

7.9 Passive Aeration

Passive aeration technology enhances the degradation of waste prior to closure of the landfill, thereby reducing degradation potential of the material following closure and likewise reducing the long-term risk to the environment. It has been implemented in Japan and other Asian countries, primarily in areas where heavy rains increase the moisture content of the waste. This technology has not yet been tried in North America or Europe. It may be applicable in parts of Northern California, where the climate is similar to some parts of Japan. There are no regulatory barriers to implementation of this technology in California. However, some air district landfill gas rules that were modeled after the Air Resources Board’s Technical Guidance for implementing 40 Code of Federal Regulations Part 60, may prohibit the passive venting of landfills directly to the atmosphere.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study does not identify any landfill sites in California that have planned or implemented passive aeration technology.

7.10 Air Injection

Air injection technology has been implemented for remediation of multiple sites in Europe to accelerate stabilization of the waste. This technology may be suitable for implementation in California. However, concerns about high temperatures and possible landfill fires plus the impact of moisture injection, often used to control high temperatures within the waste, on groundwater quality, may limit its applicability at unlined sites without geologic barriers beneath the waste.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study does not identify any landfill sites in California that have planned or implemented air injection technology.

7.11 Leachate Recirculation

Leachate recirculation is most beneficial with wastes with high organic content, and its successful application is dependent on the composition of waste at the site, local climate conditions, and local site conditions. It should generally be applicable at all lined landfill sites to reduce leachate management costs and improve leachate quality. Leachate recirculation accelerates stabilization of waste, decreasing long-term environmental risk, while increasing the potential for increased revenue from the sale of landfill gas as an energy source. Because low permeability daily cover soil can inhibit the penetration of liquid and the distribution of moisture within the waste mass, alternative daily covers may be advisable at sites where the daily cover soil is low permeability in nature. However, there do not appear to be any other barriers to leachate recirculation at lined landfill sites, and many lined sites within California recirculate leachate over lined areas for dust control.

Existing waste management regulations require the application of a final cover system within 180 days of the closure of the landfill. Unless leachate in reinjected under the final cover, the enforcement of this regulation may limit optimization of the leachate recirculation system for improving leachate quality.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study identifies six landfill sites in California that have planned or implemented leachate recirculation:

- Central Landfill
- Keller Canyon Landfill
- Vasco Road Landfill
- Acme Landfill
- Badlands Sanitary Landfill
- Potrero Hills Landfill

7.12 Landfill Mining

In general landfill mining technology is primarily applicable to sites that are confronted with the following issues.

- The site has limited airspace, and there is no local alternate waste disposal site, such that landfill mining may be implemented to increase the airspace of the facility.
- The site requires installation of a lining system or repair of an existing lining system to minimize future detrimental effects on the environment, such that landfill mining may be implemented to facilitate access to the liner.
- The existing waste unit is adversely affecting the environment (e.g., groundwater quality) and must be removed or otherwise remediated.

The application of landfill mining technology in California may be limited by the following factors.

- The waste disposed in California’s landfills may not yet be sufficiently degraded to optimize the recovery for recyclable materials.
- The market demand for recyclable materials recovered from degraded MSW may not be sufficient to economically justify implementation.

However, in high-density areas where land for disposal is scarce, landfill mining technology may be found to be a cost effective, logistically feasible, and environmentally conscious alternative. Furthermore, in cases where an existing landfill is adversely impacting the environment, landfill mining may be economically superior to other remediation options.

A review of the cross-media inventory developed as part of a previous phase of this Landfill Facility Compliance Study identifies one landfill site in California that has planned or implemented landfill mining:

- City of Clovis Landfill.

7.13 Industry Standards, Certifications, and Guidance Documents

The standards and certifications described in this study are generally applicable in California on a voluntary basis. Adherence to industry standards and self-certification can simplify regulatory oversight. Methods to provide incentives for owners to voluntarily adopt these programs may be one way to encourage further implementation of these programs. Regulatory agencies in the State of California have yet to develop guidance documents for the design of MSW landfills. As was discussed in Section 6.2, guidance documents can be beneficial in that they provide owner with a framework for design and assist regulators in ensuring quality through consistency in design methods. However, care must be taken so that the guidance document is not too prescriptive, rigid or inflexible.

Table 7-A: Summary of Technologies

		Technology Description	Global Application / Case History	Benefits	Risks/Barriers	Research Studies	Costs	Technologies in Combination
Pre-Treatment Technologies								
Mechanical Pre-Processing	**Separation**	Dividing or segregating waste by size and/or type. Options include: • Sieving/screening • Separation by hand or automatic • Physical and chemical evaluation of separated fractions	• Primarily utilized in Europe and Japan • Limited use in US at MRFs • Case History: VARGON Facility (Netherlands)	• Widely implemented as MRFs • Allows collection of recyclable materials • Flexibility of system implementation • Shortened degradation with homogenized waste • Reduction of landfilled waste mass	• Optimization requires other pre-treatment technologies, increasing cost • Integration with curbside collection of recyclables may increase cost • Potential for revenue is dependent on market rate of recyclable materials.	• Long-term effects on stabilization, gas yield, gas quality; • Full-scale comparison of MSW with different types of pre-treated wastes • Quantification of benefits • Effects of washing incinerator ash on stability • Effects of baling on biogas generation	• Relatively high capital cost and continuing operational costs	Facilitates subsequent implementation of appropriate methods for utilizing various waste components. Beneficial in combination with the following technologies: • Separation or shredding with anaerobic or aerobic pre-treatment • Mechanical pre-processing before disposal in anaerobic bioreactor. • Separation to create RDF with thermal pre-treatment (incineration)
	Size Reduction/ Shredding	Process to reduce the size of the waste particles. Types include: • Shredder • Ball mill		• Faster waste stabilization with homogenized waste • Reduction of landfilled waste	• Optimization requires other pre-treatment technologies, increasing cost			
	Washing/ Flushing	Using water to separate fine particles. Types include: • Mechanical washing - agitation of waste and water • Submerged washing - air is injected in water-waste mixture for mixing		• Better separation of particle sizes • Cleaner oversize fraction to extract reusable/recyclable materials • Washing residual from thermal pre-treatment improves environmental quality prior to disposal	• Generates a waste stream that requires treatment prior to disposal.			
	Baling	Wrapping waste to minimize exposure and increase compaction. Used for temporary storage or permanent disposal.		• Reduced short-term emissions • Lower risk of fire than loose waste for temporary storage • Cleaner landfilling operation • Increased compaction of waste, increasing capacity	• Requires changes in waste placement practices • May affect overall stability of landfill • May prolong degradation of wastes			

		Technology Description	Global Application / Case History	Benefits	Risks/Barriers	Research Studies	Costs	Technologies in Combination
Biological Pre-Treatment	**Aerobic**	Accelerated degradation in the presence of oxygen. Primary products are carbon dioxide and water. Types include: Composting piles or mechanical aeration with mixers and odor control	Small-scale applications worldwide; large-scale operations recently implemented in Europe	• Flexibility of implementation • Reduces air emissions • Minimizes long-term environmental affects • Reduction of waste mass to be landfilled	• Not applicable to wastes with low organic content • May require large area for operation • Optimization requires other pre-treatment technologies, increasing cost	• Performance of system options and methodologies • Sensitivity analyses • Evaluation of biological stability	• Large upfront capital cost • Continuing operational costs may be offset by sale of compost	Beneficial in combination with the following technologies: • separation or shredding • anaerobic pre-treatment
	Anaerobic	Accelerate degradation of waste in oxygen-deprived environment. Produces biogases that can be recovered as energy. Steps include: • Processing incoming waste • Mixing waste with water, leachate • Loading digester and increasing temperature • Residence in digester with mixing • Collection of methane • Dewatering of leachate and supplemental aerobic degradation • Disposal of residual waste in landfill	• Europe • Japan • Canada • Case History: Cagliari, Italy	• Used on all types of organic waste • Used on a variety of waste streams • Flexibility of implementation • Recovery and reuse of green energy • Potential revenue from sale of methane • Minimizes long-term environmental affects • Reduction of waste mass to be landfilled	• Not applicable to wastes with low organic content • Space needed for facility • Optimization requires other pre-treatment technologies, increasing cost • Active odor controls required during and after anaerobic digestion	• Performance of system options and methodologies • Sensitivity analyses • Quantification of organic degradation and gas generation • Effects of pre-treatment on emissions quality improvement	• Large upfront capital cost • Continuing operational costs may be offset by sale of methane and energy conversion	Beneficial in combination with the following technologies: • separation or shredding • aerobic pre-treatment

		Technology Description	Global Application / Case History	Benefits	Risks/Barriers	Research Studies	Costs	Technologies in Combination
Thermal Pre-Treatment	Incineration	Complete combustion of MSW resulting in the production of bottom ash and fly ash. Energy can be produced in the form of steam, which is fed to a turbine. Can also be used for cement manufacture. Components of system include: • Refuse receiving, handling and storage systems • Combustion and steam generation systems • Flue gas cleaning system • Power generation equipment • Cooling water condenser • Residue hauling and storage system	• Europe • Japan • North America • Approximately 112 facilities in the U.S. that process nearly 32 million tons of MSW annually	• Potential revenue from sale of energy • Reduction of waste mass to be landfilled • Reduction of landfill gas emissions • RDF process allows recovery of recyclable materials • Potential to use by-products as construction material	• Not applicable to construction debris or inert material • Air quality concerns • Optimization requires other pre-treatment technologies, increasing cost • Untreated residual waste may be considered hazardous • Long-term environmental impacts of disposed residual • Potential revenue from energy production is subject to market volatility • On-going maintenance and repair	• Leaching potential of residual ash, • benefit comparison to other pre-treatment options, • emissions potential from various MSW waste streams, • performance of individual components, • physical characteristics of residual ash, • effect on biological stability, • structural and environmental impact of using residual ash in construction.	• Very large upfront capital cost • Continuing operational costs may be offset by sale of energy	Beneficial in combination with separation and/or shredding
	Pyrolysis	Degradation of waste in a controlled environment at high temperatures in the absence of oxygen. Limits the combustion of input materials and produces potentially recoverable gases, oils, and solids, in addition to heat and ash. Primarily used to treat agricultural and forestry residues, MSW, and post-recycling residues.	More than 100 small facilities worldwide, most of which are less than 5 years old	• Potential revenue from sale of by-products • Reduction of waste mass to be landfilled • Eliminates uncontrolled air emissions	• Not applicable to construction debris or inert material • Optimization requires other pre-treatment technologies, increasing cost • Potential revenue from energy production is subject to market volatility • On-going maintenance • Most facilities are less than 5 years old and long-term effects are unknown • Unproven on a large commercial scale	• Comparison of long-term effects of high-temperature waste to bottom ash • Structural considerations and environmental impacts of using waste-derived construction material	• Very large upfront capital cost • Continuing operational costs may be offset by sale of waste-derived materials	

	Technology Description	Global Application / Case History	Benefits	Risks/Barriers	Research Studies	Costs	Technologies in Combination
Landfill Design Technologies							
Anaerobic Bioreactor	Liquid injected in a controlled fashion into the waste mass in order to accelerate or enhance biostabilization of the waste. Components include: • liquid injection system, • gas collection system, and • emissions monitoring system.	Several European countries, Canada and the U.S. are beginning to accept bioreactor technology.	• Reduced post-closure maintenance. • Increased revenue from sale of landfill gas. • Improved performance of final cover system. • Increased air space. • Lower leachate treatment and disposal costs. • Improved leachate quality with time. • Decrease in long-term environmental risk.	• Increased complication and associated cost of design. • Not applicable to all sites. • Increase in potential for stability problems. • Increased dependence on LCRS, liner system and gas collection system.	• Landfill gas production rates. • Water balance effects on biodegradation. • Anaerobic digestion and biodegradation rates. • Temperature effects on waste degradation. • Nutrient content of leachate. • Management of nitrogen in leachate.	• Moderate increase in construction and operations cost • Continuing operational costs may be offset by sale of methane or energy • Potential for increased revenue from waste liquids	Particularly beneficial in combination with the following technologies: • aerobic pre-treatment • air injection • mechanical pre-processing
Aerobic / Semi-Aerobic Landfill	Introduction of air into landfill allows accelerated aerobic degradation. Two types: passive aeration (semi-aerobic landfill) and air injection (aerobic landfill)	Three sites identified in U.S.: • Columbia County Baker Place Landfill (Georgia) • Live Oak Landfill (Georgia) • New River Landfill (Florida) Numerous sites in Japan and the Far East	(refer to Remediation Technologies: Passive Aeration and Air Injection)				

		Technology Description	Global Application / Case History	Benefits	Risks/Barriers	Research Studies	Costs	Technologies in Combination
Alternative Base Containment Systems	**Double Liners**	Prescriptive single composite liner underlain by leak detection system and second liner	• Required for MSW in several states • Used throughout the U.S. for hazardous waste landfills	Provides a higher level of containment than single prescriptive single composite liner system	Significantly more expensive to construct than prescriptive liner		$3 to $4 per square foot of liner (typical)	Can be used with inward gradient landfill if no geomembrane in secondary liner.
	Electrically-Conductive Liners	Conductive underside of geomembrane allows detection of holes during liner construction	Numerous applications in the U.S. and worldwide	Provides additional method for ensuring construction quality	• More expensive than non-conductive geomembrane • Not applicable with double-sided textured geomembrane or encapsulated GCL • Only large holes are detected		$0.05 per square foot of liner (typical)	Cannot be used in combination with encapsulated GCL
	White Liners	White geomembrane used in lieu of typical black geomembrane in composite liner systems	Numerous applications in the U.S. and worldwide	• Minimizes affect of wrinkles • Reduces surface temperature on liner during installation • Simplifies CQA			$0.03 to $0.05 per square foot of liner	
	Tensioned Liners	Liner is tensioned during installation and protected (shaded) from direct sunlight	Used widely in Germany	Minimizes / eliminates wrinkles	• Greatly complicates installation • Considerable more expensive to install		Reported to be significant additional cost for liner installation	
	Encapsulated GCL	Membranes are placed above and below GCL to minimize hydration	At least 6 landfills in California	• Minimizes GCL hydration, increasing internal shear strength • Provides additional membrane barrier to advective leachate transport	Considerably more expensive to install than single composite liner system		$0.10 to $0.35 per square foot, depending on method of encapsulation	Cannot be used in combination with electrically-conductive geomembrane

		Technology Description	Global Application / Case History	Benefits	Risks/Barriers	Research Studies	Costs	Technologies in Combination
Alternative Base Containment Systems	**Inward Gradient Landfill**	Landfill constructed below groundwater table, redirecting groundwater flow toward landfill cell	• Canada • Case History: Gray Wolf Regional Landfill (Arizona)	• Increased prevention of leakage through liner • Potential for reduced long-term care of cover and LCRS	• Applicable only to sites with high groundwater • Difficulty gaining regulatory approval • Uncertainty of long-term groundwater conditions • Potential for large volumes of liquid to be handled (and treated)			Can be used with double liner system with no geomembrane in secondary liner
Alternative Cover Systems	**Monolithic ET Cover Systems**	Monolithic soil cover designed to minimize infiltration through storage capacity and evapotranspiration characteristics of soil layer	• Over one dozen sites in southwestern U.S. • Case History: Yucaipa Landfill (California)	• Cost savings over prescriptive cover • Ease of construction • Less susceptible to cracking • Cover allowed to breathe • Enhanced veneer stability • Accelerates waste stabilization • Easier post-closure development	• Performance dependent on proper design (modeling) • Applicability dependent on climate and availability of suitable soil • Allows deeper rooted vegetation • Requires performance demonstration for regulatory approval	Nationwide wide studies on alternative cover systems: • Alternative Landfill Cover Demonstration by DOE • Alternative Cover Assessment Program by USEPA		
	Capillary Break Cover System	Evapotranspirative cover using layering sequence to minimize infiltration through capillary suction	• Several locations in U.S. • Case History: Gaffey Street Landfill (California)	• Cost savings over prescriptive cover • Less susceptible to cracking • Provides gas collection layer • Enhanced veneer stability • Accelerated waste stabilization	• Performance dependent on proper design (modeling) • "Break through" can result in large infiltration • Applicability dependent on climate, site configuration, and availability of soil • Requires demonstration for regulatory approval	Nationwide wide studies on alternative cover systems: • Alternative Landfill Cover Demonstration by DOE • Alternative Cover Assessment Program by USEPA		

		Technology Description	Global Application / Case History	Benefits	Risks/Barriers	Research Studies	Costs	Technologies in Combination
Alternative Cover Systems	Phytoremediation Cover System	Monolithic evapotranspiration cover systems designed to utilize vegetation to minimize infiltration and accelerate degradation	• Applied worldwide Up to 18 sites in U.S.	• Less susceptible to cracking • Enhanced veneer stability • Allows deeper rooted vegetation	• Not applicable if large quantity of landfill gas expected to be generated • Applicability dependent on climate, site configuration, and availability of soil • Requires demonstration for regulatory approval • Long-term maintenance of vegetation	Nationwide wide studies on alternative cover systems: • Alternative Landfill Cover Demonstration by DOE • Alternative Cover Assessment Program by USEPA		
	Exposed Geomembrane Cover System	Cover consists of geomembrane over foundation layer with no surface soil layer for limited-term application	• Four sites identified in U.S. Case History: Delaware Solid Waste Authority Site	• Cost savings over prescriptive cover • Reduced annual O&M costs • Easier access for repair and inspection • Reduced post-closure settlement • Reduced hydraulic head on geomembrane cover • No veneer stability issues	• Increased vulnerability to environmental damage • Increase peak surface water discharge • Susceptibility to wind and landfill gas uplift • Limited vehicle access • Limited design life may require full replacement • Aesthetic concerns • Limited options for post-closure use			
	Delayed Closure	Construction of final cover delayed to allow continued degradation of wastes		• Reduced post-closure environmental impacts • Reduced post-closure settlement of cover system • Reduced post-closure maintenance • Potential for shortened post-closure care period • Improved performance of cover system • Decrease in long-term environmental risk due to accelerated stabilization	• Not applicable to all sites • Increased potential for pre-closure environmental impacts • Requires regulatory approval			

		Technology Description	Global Application / Case History	Benefits	Risks/Barriers	Research Studies	Costs	Technologies in Combination
Remediation Technologies								
Landfill Gas Applications	Destruction	Destruction through: • High-temperature flare • Noncatalytic oxidation	• Chapois Landfill, Belgium • None in U.S.	• Methane almost completely oxidized • May be designed to continuously analyze concentrations	• Untried • High capital cost	• Comparison of performance to US regulations recommended		Particularly beneficial in combination with the following technologies: • anaerobic bioreactor • leachate recirculation
	Electricity	Conversion using: • Internal combustion reciprocating engines • Combined cycle plants • Microturbines • Fuel cells • Stirling cycle engines	Application varies by type. Refer to Section 5.1.2.2.	• Beneficial reuse of landfill by-product • Reduces greenhouse emissions associated with destruction of LFG • Economic incentives: emissions credits, tax credits and revenue	• High capital cost • Revenue may fluctuate • Incentives may limited or uncertain	Research varies by type. Refer to Section 5.1.2.3		Particularly beneficial in combination with the following technologies: • anaerobic bioreactor • leachate recirculation
	Medium Btu Fuel	Direct use of LFG in boilers, incinerators, and space heaters	Various locations in U.S., Canada and U.K.	• Beneficial reuse of landfill by-product • Reduces greenhouse emissions associated with destruction of LFG • Low capital cost and O&M • Economic incentives: emissions credits, tax credits and revenue	• User should be within 1 mile of landfill to keep cost low			Particularly beneficial in combination with the following technologies: • anaerobic bioreactor • leachate recirculation
	High Btu Fuel	Purification of LFG for use as industrial or commercial fuel	• Puente Hills Landfill, California • France, Iceland, Canada	• Beneficial reuse of landfill by-product • Reduces greenhouse emissions associated with destruction of LFG • LNG and CNG are cleaner burning than gas or diesel • Natural gas vehicles have lower maintenance costs • Economic incentives: emissions credits, tax credits and revenue	• High capital cost • Purification technologies expensive • Natural gas market volatile • Regulatory restraints may limit offsite distribution • Natural gas vehicles less attractive to consumers	Research projects: • Ultra-sound liquefaction of methane as alternative method for purification • Small conversion units for use at low LFG producing sites		Particularly beneficial in combination with the following technologies: • anaerobic bioreactor • leachate recirculation

		Technology Description	Global Application / Case History	Benefits	Risks/Barriers	Research Studies	Costs	Technologies in Combination
Landfill Gas Applications	Leachate Evaporation	Injection of leachate into LFG flare	• Olympic View Sanitary Landfill, Washington • 12 sites in Texas • Lorain County 1 Landfill, Ohio	• May reduce impact and cost of handling and disposing leachate • Tax credits	• Emission of volatiles and metals if combustion incomplete		Unit plus ancillary equipment: $50,000 to $100,000	
	Industrial Products	Carbon dioxide extraction use in industrial applications	• Al Turi Landfill, NY • EcoComplex, NJ	• Beneficial reuse of landfill by-product • Reduces greenhouse emissions associated with destruction of LFG • Potential revenue	• LFG supply for 10 to 15 years for cost viability • Markets for products must be available	No commercial scale demonstration yet performed		Particularly beneficial in combination with the following technologies: • anaerobic bioreactor • leachate recirculation
Passive Aeration		Introduction of air under ambient conditions develops semi-aerobic condition to accelerate the degradation of waste	• Japan • Malaysia • Iran • None identified in Europe or US • Case History: Yamato Kataku Landfill (Japan)	• Low up-front costs • Low O&M costs • Increased airspace • Reduced generation of methane • Decrease in long-term environmental risk	• Performance depends on moisture content of waste • Applicability depends on climate, waste characteristics and site configuration • LCRS may be susceptible to bio-clogging • Untried in US and Europe	• Effects on gas generation, leachate generation and leachate composition • Comparative evaluation with other technologies • Quantization and optimization of air flow for aerobic degradation		Particularly beneficial in combination with leachate recirculation
Air Injection		Introduction of air under pressure develops aerobic condition to accelerate degradation of waste	• Italy • Germany • Case History: Kuhstedt Landfill (Germany)	• Increased airspace • Reduced generation of methane • Improved leachate quality • Improved performance of final cover • Short treatment period • Potential for shortened post-closure period • Decrease in long-term environmental risk	• Increased risk for landfill fires • Increased leachate generation • Increased explosive risk • Limited applicability based on waste characteristics, climate, and site configuration • Higher operational costs for air injection than for operation of other technologies • Potential for odor due to surface break through	• Effects on gas generation, leachate generation and leachate composition • Comparative evaluation with other technologies • Evaluation of degradation rates under aerobic conditions • Quantization and optimization of air flow for aerobic degradation	• Moderate increase in capital costs for new landfill • Large capital cost for retrofit or remediation • Higher operational costs for air injection than for operation of other technologies	Particularly beneficial in combination with the following technologies: • Bioreactor • Leachate recirculation

	Technology Description	Global Application / Case History	Benefits	Risks/Barriers	Research Studies	Costs	Technologies in Combination
Leachate Recirculation	Leachate injection into an existing landfill cell for the primary purpose of handling leachate generated at the site. Components include: • liquid injection system, • gas collection system, and • emissions monitoring system.	Application at numerous sites nationwide and in several European countries and South Africa. Several instances of landfill instability. Case Histories – Bulbul Drive, South Africa, Columbia, South America, and Ohio of failures resulting from poorly controlled reinjection.	• Potential revenue from sale of methane • Improved performance of final cover system • Increased air space • Lower leachate treatment and disposal costs • Improved leachate quality with time • Decrease in long-term environmental risk	• Increased complexity and associated cost of design • Not applicable to all sites • Waste heterogeneity can cause preferential flow • Increase in potential for stability problems • Increased dependence on LCRS, liner system and gas collection system	• Effects of leachate composition on quality improvement • Observation of emissions • Laboratory decomposition studies • Effects of waste processing • Movement of liquid through waste mass • Evaluation of time frame over which leachate contamination can occur given the improvements in leachate quality from leachate recirculation • Reduction in mobilized shear strength due to increased moisture	• Small to moderate increase in capital cost • Increased operational cost offset by reduction in leachate treatment costs	Particularly beneficial in combination with the following technologies: • Aerobic pre-treatment • Mechanical pre-processing • Passive aeration • Air injection
Landfill Mining / Waste Recycling	Previously landfilled solid wastes are excavated and processed to recover recyclables, a combustible fraction, soil and/or landfill airspace. Typically applied to sites where there is limited airspace and no alternate waste disposal site is available, or when a site requires installation of a lining system.	Several sites in the U.S. and one in Israel have implemented landfill mining	• Reclaims used airspace • Allows for installation or repair of lining system • Recovery and recycling of materials • Potential revenue from recycled materials • Reuse of residual material as daily cover • Reduced post-closure costs • Flexibility in implementation • Reduces/eliminates impact of unlined waste units	• Potential hazards to mining personnel • Increased odors / emissions • Increased operational monitoring; • Potential for cost to outweigh benefit • Upfront capital for design and construction of sorting facility • Cost effectiveness dependent of the market demand for recycled materials • Recovered materials are low quality	Very little existing or on-going research regarding landfill mining has been identified. Further evaluation of experiences at existing sites is recommended if this technology is to be considered for application.	• Very large capital cost • No continuing operational cost	Particularly beneficial in combination with the following technologies: • Aerobic landfill • Exposed Geomembrane Cover System

	Technology Description	Global Application / Case History	Benefits	Risks/Barriers	Research Studies	Costs	Technologies in Combination
Industry Standards, Certifications and Guidance Documents							
Standards	Industry standards for equipment, processes, environmental safety and personnel requirements (such as ANSI Standards)	Voluntary implementation nationwide	Allows for self-regulation by industry	Requires commitment from operators and nominal cost to implement and maintain		Small to none	
Certifications	Certification of facilities and facility personnel through compliance with independent programs (i.e., ISO 14001, SWANA Certification Programs)	• Mandatory in some European countries • Voluntary implementation in U.S. waste industry	• Allows self-regulation of industry • Potential for reduced emissions • Simplifies improvement of systems • Potential for lower long-term costs • May result in enhance corporate reputation for operators	Requires up front cost to implement programs and train personnel		• Moderate cost to establish program and bring operations into compliance • Increased record keeping costs	
Guidance Documents	Documents developed by regulatory agencies to guide engineers in design process and owners in landfill operations	Ohio EPA	• Provide owners and designers with framework for design • Assist regulators with review, improving quality and consistency	• One-time cost to regulators • Care must be taken to ensure document is not too rigid		• One-time cost to develop guidance document • Minimal increased cost to operators	

Table: 7-B: Application of Technologies in California

Technology	Application in California
Pre-Treatment Technologies	
Mechanical Pre-Processing	
Separation	• Currently being implemented at MRFs. • Difficulty quantifying cost vs. benefit limits widespread application
Size Reduction/ Shredding	• Currently being implemented at MRFs. • Difficulty quantifying cost vs. benefit limits widespread application
Washing/ Flushing	• Difficulty quantifying cost vs. benefit limits widespread application • Wastewater stream generally requires processing
Baling	• Difficulty quantifying cost vs. benefit limits widespread application
Biological Pre-Treatment	
Aerobic	• Applicability based on waste content • Greenwaste diversion may impact benefits, potential • Difficulty quantifying cost vs. benefits limits widespread application.
Anaerobic	• Applicability based on waste content • Greenwaste diversion may impact benefits, revenue • Difficulty quantifying cost vs. benefits limits widespread application.
Thermal Pre-Treatment	
Incineration	• Implemented at several sites in California • Cost and revenue dependent on waste composition • Air regulations may preclude application • Potential for long-term impacts of ash may restrict disposal options
Pyrolysis	• Unknown cost • No record of large-scale application; may limit application
Landfill Design Technologies	
Anaerobic Bioreactor	• Applicability dependent on waste content, site climate and water supply • No previous approval at sites with GCL liner system • Greenwaste diversion may impact benefits, revenue • Extent of degradation may be limited by closure requirements
Aerobic/ Semi-Aerobic Landfill	(refer to Remediation Technologies: Passive Aeration and Air Injection)
Alternative Base Containment Systems	
Double Liners	• Significant cost with questionable environmental benefit • May be beneficial at sites with unusual site conditions

Technology	Application in California
Electrically-Conductive Liners	• Will not detect small defects • May not be necessary with good CQA
White Liners	• Being used with increasing frequency • Particularly useful in hot climates
Tensioned Liners	• High cost with questionable environmental benefit
Encapsulated GCLs	• Already employed at several sites • Particularly useful for canyon side slopes
Inward Gradient Landfill	• State and Federal regulations may preclude application • Applicable only to sites with high groundwater
Alternative Cover Systems	
Monolithic ET Cover Systems	• Already employed at a number of sites • Most applicable to arid / semi-arid climates • Conditional regulatory approval discourages application
Capillary Break Cover System	• Additional cost may not be warranted • Most applicable to arid / semi-arid climates • Conditional regulatory approval discourages application
Phytoremediation Cover System	• Still a developing technology • Conditional regulatory approval discourages application
Exposed Geomembrane Cover System	• Applicable for limited-term capping (10-20 years) • Not applicable for sites with high winds or aesthetics standards
Delayed Closure	• Applicability depends on waste characteristics, climate and base containment system at site
Remediation Technologies	
Landfill Gas Applications	
Destruction	• Untried in U.S. • A comparison of performance and emissions to state and federal regulations should be performed
Electricity	• All methods have been tried in California • Quantity of LFG critical in evaluating viability; may not be applicable in arid climates • Air quality standards may limit implementation • State regulations promote the use of renewable fuel sources • Favorable response expected from consumers
Medium Btu Fuel	• No significant hurdles from economic or regulatory standpoint
High Btu Fuel	• Revenue limited by California testing requirements of LFG distributed offsite • Viability will increase as demand for natural gas increases
Leachate Evaporation	• Not universally accepted • Permitting challenges anticipated in air quality non-attainment areas
Industrial Products	• No significant hurdles from economic or regulatory standpoint • Commercial scale application has not been performed in US

Technology	Application in California
Passive Aeration	• Most applicable to wet climates • Untried in the U.S.
Air Injection	• Applicability limited by base containment configuration • Applicability dependent on moisture content of waste • Unsuccessful application in Georgia
Leachate Recirculation	• Widely used • Requires injection of leachate under final cover system to continue after closure
Landfill Mining / Waste Recycling	• Applicable to sites with limited airspace • Applicable to sites that require installation or repair of liner • Applicable to sites adversely impacting environment • Waste must be sufficiently degraded • Limited market for recycled material may preclude application • Most applicable in high-density areas
Industry Standards, Certifications and Guidance Documents	
Standards	• Generally applicable in California • Voluntary • Can simplify regulatory oversight • Regulatory incentives may encourage implementation
Certifications	• Generally applicable in California • Voluntary • Can simplify regulatory oversight • Regulatory incentives may encourage implementation • No evidence that lack of certification compromises environmental protection
Guidance Documents	• No guidance documents are currently available in California • Site-specific conditions may impact applicability of guidance procedures

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